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InGaAsP-on-Insulator Platform for Nonlinear Photonic Applications: Design, Fabrication, and Challenges

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Declaration of Authorship

I, Rania Mahjoub, declare that this thesis, titled InGaAsP-on-Insulator Platform for Nonlinear Photonic Applications, and the work presented in it are my own. I confirm that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

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Abstract

Integrated photonics has emerged as a promising technology for realizing compact, high-speed, and energy-efficient optical systems for applications including optical communications, nonlinear signal processing, and photonic computing. Among the available integrated photonic material platforms, III–V semiconductors are particularly attractive because of their direct bandgap properties, strong optical nonlinearities, and capability for integrating active and passive photonic devices on a single chip. In particular, indium gallium arsenide phosphide (InGaAsP) offers tunable bandgap engineering and compatibility with operation near telecommunication wavelengths, making it a promising candidate for nonlinear integrated photonics.

This thesis investigates the development of an InGaAsP-on-insulator (InGaAsP-OI) platform through heterogeneous integration using benzocyclobutene (BCB) adhesive wafer bonding. The work addresses both fabrication challenges and nonlinear waveguide design for two distinct nonlinear processes at telecommunications-relevant wavelengths. The fabrication process includes SiO_2 deposition, BCB bonding, substrate transfer, selective wet etching, and structural characterization of the bonded platform.

Particular attention is given to fabrication-induced limitations affecting the reliability and optical performance of the InGaAsP-OI platform. Experimental characterization using scanning electron microscopy (SEM), atomic force microscopy (AFM), and energy-dispersive X-ray spectroscopy (EDX) is used to investigate surface roughness, bonding quality, interfacial defects, and delamination mechanisms associated with the BCB/ SiO_2 interface.

In addition, nonlinear InGaAsP-OI waveguides are designed and analyzed numerically for two complementary processes. First, dispersion-engineered waveguides for four-wave mixing (FWM) are optimized using Lumerical MODE simulations, achieving a zero-dispersion wavelength of 1553 nm and a nonlinear coefficient of $\gamma \approx 36.9 \text{ W}^{-1}\text{m}^{-1}$ for the optimized geometry ($w = 830 \text{ nm}$, $h = 800 \text{ nm}$). Second, modal phase-matching-based second-harmonic generation (SHG) is investigated at a fundamental wavelength of $2.6 \mu\text{m}$, exploiting the non-centrosymmetric zinc-blende crystal structure of InGaAsP to achieve $\chi^{(2)}$ -based frequency conversion without additional quasi-phase-matching structures. A phase-matched waveguide

geometry is identified through analytical mode simulations, and the modal overlap and SHG conversion efficiency are quantified.

The results demonstrate the potential of InGaAsP-OI structures for compact, chip-scale nonlinear photonic circuits operating at telecommunications wavelengths, while highlighting the critical role of fabrication optimization and bonding reliability in the development of practical III–V-on-insulator nonlinear photonic platforms.

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List of Abbreviations

InP	Indium Phosphide
InGaAsP	Indium Gallium Arsenide Phosphide
InGaAsP-OI	Indium Gallium Arsenide Phosphide On Insulator
AlGaAs	Aluminium Gallium Arsenide
AlGaAs-OI	Aluminium Gallium Arsenide On Insulator
SOI	Silicon on Insulator
CMOS	Complementary Metal-Oxide-Semiconductor
FWM	Four-Wave Mixing
SHG	Second-Harmonic Generation
SFG	Sum-Frequency Generation
DFG	Difference-Frequency Generation
n_2	Nonlinear refractive index
DI	Deionized water
HCl	Hydrochloric acid
H₃PO₄	Phosphoric acid
BCB	Benzocyclobutene
PECVD	Plasma-Enhanced Chemical Vapor Deposition
MBE	Molecular Beam Epitaxy
MOCVD	Metal-Organic Chemical Vapor Deposition
SPM	Self-Phase Modulation
XPM	Cross-Phase Modulation
GVD	Group-Velocity Dispersion
GVM	Group-Velocity Mismatch
FSR	Free Spectral Range
CW	Continuous Wave
TE	Transverse Electric
TM	Transverse Magnetic
SEM	Scanning Electron Microscope

AFM	Atomic Force Microscope
ICP	Inductively Coupled Plasma
RIE	Reactive Ion Etching
FDTD	Finite-Difference Time-Domain
FEM	Finite Element Method
BPM	Beam Propagation Method
TPA	Two Photon Absorption
OPO	Optical Parametric Oscillator

Chapter 1

Introduction

1.1 Integrated Photonics and Material Platforms

Integrated photonics has emerged as a key technology for enabling compact, high-performance optical systems across a wide range of applications, including optical communications [1], sensing, signal processing [2], and quantum technologies [3]. By integrating multiple optical components onto a single chip, photonic integrated circuits (PICs) offer significant advantages in terms of scalability, stability, energy efficiency, and cost reduction compared to discrete optical systems [4].

A challenge in integrated photonics is the selection of suitable material platforms that balance optical performance, fabrication complexity, and functionality. Several platforms have been extensively developed, including silicon-on-insulator (SOI) [5], silicon nitride (Si_3N_4), lithium niobate (LiNbO_3) [6], and III–V compound semiconductors [7]. Each platform offers distinct advantages and limitations.

Silicon-on-insulator has become the dominant platform for large-scale photonic integration due to its high refractive index contrast, enabling strong optical confinement, compact device footprints, and compatibility with CMOS fabrication processes [8]. However, silicon suffers from an indirect bandgap, which prevents efficient light emission. Furthermore, its bandgap energy limits photodetection at telecommunications wavelengths, making III–V semiconductors the preferred choice for integrated light sources and detectors in this spectral range [9].

Silicon nitride, in contrast, offers ultra-low propagation loss and negligible two-photon absorption at telecommunications wavelengths, making it highly suitable for linear and low-loss applications [10]. However, its relatively weak nonlinear response and lack of active functionality restrict its use in applications requiring optical gain or strong nonlinear interactions [4].

Lithium niobate has gained renewed attention due to its strong second-order nonlinearity and electro-optic properties, enabling efficient modulation and frequency conversion [11, 12]. Despite these advantages [13], its integration density and fabrication complexity remain challenges.

In comparison, III–V compound semiconductors, such as InP [14], GaAs [15], AlGaAs [16], and InGaAsP [14], occupy a unique position in integrated photonics. These materials possess a direct bandgap, enabling efficient light emission, amplification, and detection [16]. This makes them particularly well-suited for the monolithic integration of active and passive devices, including lasers, modulators, photodetectors, and waveguides [17, 18, 8].

Among III–V materials, InGaAsP is especially attractive due to its tunable bandgap, which allows operation across telecommunications wavelengths (1.3–1.55 μm), as well as its favorable nonlinear optical properties [10]. These characteristics make it a strong candidate for both active photonic devices and nonlinear optical applications.

Despite their advantages, traditional III–V platforms are typically grown on native substrates (e.g., InP), resulting in relatively low refractive index contrast [14]. This limits optical confinement and increases device footprint. Additionally, integration with silicon-based platforms remains challenging.

To address these limitations, III–V-on-insulator platforms have been developed, combining the superior optical properties of III–V materials with the high index contrast and scalability of insulator-based systems. In particular, AlGaAs-on-insulator has demonstrated excellent performance for nonlinear photonics [19, 15], motivating further exploration of alternative III–V materials.

Building on this progress, InGaAsP-on-insulator (InGaAsP-OI) platforms have recently attracted attention due to their strong Kerr nonlinearity, tunable bandgap, and compatibility with telecommunications applications [20]. By bonding thin InGaAsP layers onto SiO_2/Si substrates, high optical confinement [21] and enhanced nonlinear interaction efficiency can be achieved.

This thesis focuses on the development and analysis of InGaAsP-on-insulator platforms with particular emphasis on bonding techniques and waveguide design for nonlinear photonic applications.

1.2 Waveguide Optics

Optical waveguides are fundamental components of photonic integrated circuits because they enable the confinement and routing of light between different optical elements on a chip [14]. Achieving low-loss optical propagation is a critical requirement in integrated photonics, as

propagation losses and nonlinear effects directly influence device performance and signal integrity [14].

As light propagates through a waveguide, it can experience several physical effects, including self-phase modulation (SPM), group velocity dispersion (GVD), scattering loss, and material absorption. Scattering and absorption contribute to optical attenuation, while dispersion and nonlinear phase modulation alter the temporal and spectral characteristics of the optical signal. Understanding these mechanisms is therefore essential for the analysis and design of integrated photonic devices.

Various waveguide geometries are used in integrated photonics, including buried strip, ridge, rib, embedded, and strip-loaded waveguides. These structures differ in their confinement characteristics, fabrication complexity, and modal properties. Among them, the dielectric slab waveguide provides a useful starting point for understanding electromagnetic mode confinement and propagation in optical waveguides. Different waveguide geometries commonly used in integrated photonics are illustrated in Figure 1.1 and 1.2. The optical confinement and modal properties of these structures strongly depend on the refractive index contrast and waveguide geometry.

The propagation of electromagnetic waves in dielectric waveguides is governed by Maxwell's equations with appropriate boundary conditions:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \quad (1.1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (1.2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1.3)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \quad (1.4)$$

where $\mathbf{E}$ and $\mathbf{B}$ represent the electric and magnetic fields, ρ is the electric charge density, $\mathbf{J}$ is the current density, ε_0 is the vacuum permittivity, and μ_0 is the vacuum permeability. These equations form the foundation for describing optical mode propagation, confinement, and dispersion in dielectric waveguide structures [22].

$$\nabla^2 \mathbf{E} - \frac{n^2}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = \nabla (\mathbf{E} \cdot \nabla \ln n^2) \quad (1.5)$$

For waveguides where the refractive index contrast is smooth in the transverse plane, the right-hand side is small and the scalar approximation is valid. Assuming a monochromatic

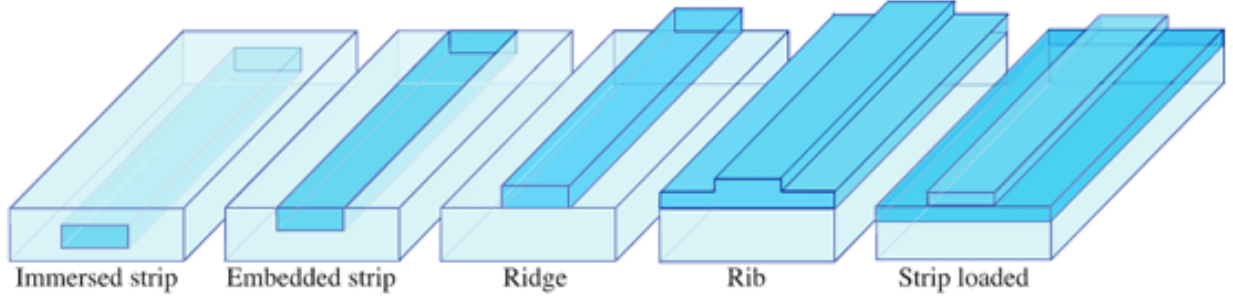


Figure 1.1: Two-dimensional channel waveguide geometries, where the darker regions indicate a higher refractive index. From left to right: immersed/buried strip waveguide, embedded strip waveguide, ridge waveguide, rib waveguide, and strip-loaded waveguide [22].

field varying as $\exp(i\beta z - i\omega t)$, where β is the propagation constant and z is the axis of propagation, the transverse field distribution $\psi(x, y)$ satisfies the eigenvalue equation:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \psi + [k_0^2 n^2(x, y) - \beta^2] \psi = 0 \quad (1.6)$$

where $k_0 = \omega/c = 2\pi/\lambda$ is the free-space wavenumber. Solutions to this equation are the guided modes of the waveguide structure. Each mode is characterised by its propagation constant β_m , from which the effective refractive index is defined as:

$$n_{\text{eff}} = \frac{\beta_m}{k_0} \quad (1.7)$$

For a guided mode to exist, the condition

$$n_{\text{clad}} < n_{\text{eff}} < n_{\text{core}} \quad (1.8)$$

must be satisfied, which ensures total internal reflection at the core-cladding boundary.

1.2.1 polarization and Mode Classification

In channel waveguides, the modes are classified as quasi-TE (transverse electric) or quasi-TM (transverse magnetic). TE modes have their dominant electric field component oriented along the horizontal axis (E_x dominant), while TM modes have the dominant component along the vertical axis (E_y dominant).

The TE and TM modes exhibit different confinement factors and dispersion profiles because of the asymmetric boundary conditions imposed by the waveguide geometry. For InGaAsP-OI waveguides with a refractive index of approximately 3.35 and a lower-cladding refractive index of 1.44 taken as that of SiO₂, with the thin BCB bonding layer neglected in

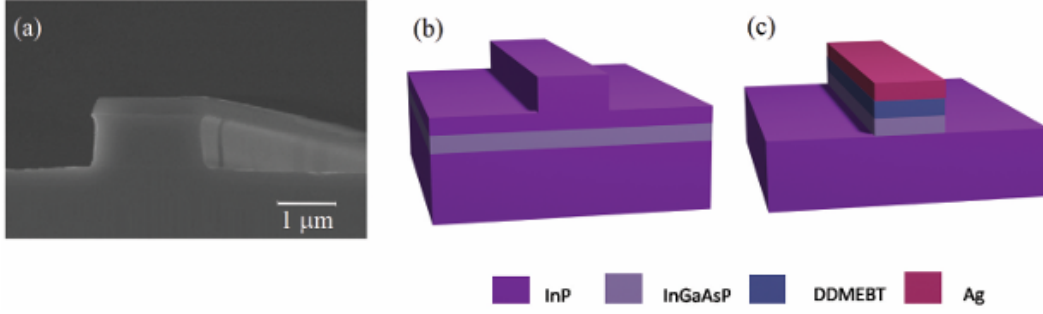


Figure 1.2: Examples of InGaAsP waveguide structures. (a) Scanning electron microscope (SEM) image of an InGaAsP strip-loaded waveguide facet. (b) Schematic illustration of a strip-loaded slab-type InGaAsP waveguide, where optical confinement is achieved through partial lateral index guiding without full etching of the guiding layer. (c) Schematic illustration of an InP-based hybrid plasmonic channel/ridge waveguide providing strong lateral and vertical optical confinement [23].

this simplified treatment the TE mode is generally more strongly confined due to the larger index step experienced by the horizontally polarized field. This polarization dependence is important for dispersion engineering and phase-matching in nonlinear applications.

1.2.2 Optical Dispersion in Waveguides

Dispersion describes the dependence of the phase velocity on optical frequency and is one of the most critical parameters for nonlinear photonic devices. It can be decomposed into two contributions: material dispersion, arising from the intrinsic frequency dependence of the refractive index $n(\omega)$ of the guiding medium, and waveguide dispersion, arising from the geometry-dependent variation of the modal confinement with frequency.

The propagation constant $\beta(\omega)$ is expanded in a Taylor series around the pump frequency ω_0 :

$$\beta(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \frac{1}{6}\beta_3(\omega - \omega_0)^3 + \dots \quad (1.9)$$

where $\beta_1 = 1/v_g$ is the inverse group velocity and

$$\beta_2 = \frac{d^2\beta}{d\omega^2} \quad (1.10)$$

is the group velocity dispersion (GVD) parameter, also written as:

$$\beta_2 = -\frac{\lambda^2}{2\pi c}D \quad (1.11)$$

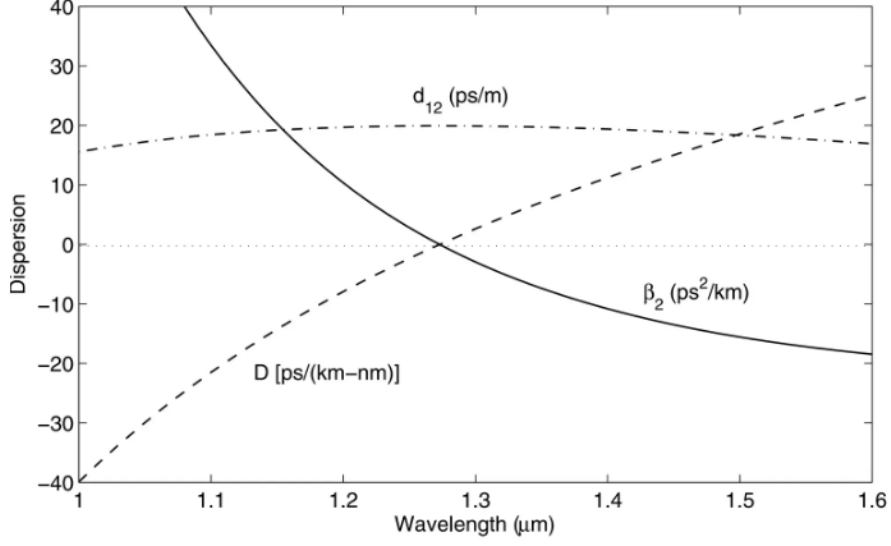


Figure 1.3: Typical group velocity dispersion (β_2) and dispersion parameter (D) as functions of wavelength in silica optical fibers, illustrating the transition between normal and anomalous dispersion regimes and the zero-dispersion wavelength (adapted from [24]).

with D the dispersion parameter in units of $\text{ps}/(\text{nm}\cdot\text{km})$.

The sign of β_2 determines the dispersion regime. Anomalous dispersion ($\beta_2 < 0$) is required for broadband phase matching in many nonlinear processes, including modulation instability and four-wave mixing, while normal dispersion ($\beta_2 > 0$) tends to suppress parametric gain. The wavelength at which $\beta_2 = 0$ is known as the zero-dispersion wavelength (ZDW). Engineering the ZDW near the pump wavelength is therefore one of the primary goals of nonlinear waveguide design.

In high-index-contrast waveguides such as InGaAsP-on-insulator, the waveguide dispersion contribution is large and can be tuned by adjusting the waveguide dimensions. Increasing the waveguide width shifts the ZDW toward longer wavelengths for the TE mode, while the TM mode is generally less sensitive to geometry changes because of its weaker lateral confinement. Figure 1.3 illustrates the variation of group velocity dispersion with wavelength, highlighting the transition between the normal and anomalous dispersion regimes as well as the zero-dispersion wavelength, which plays a critical role in nonlinear optical interactions such as four-wave mixing.

1.2.3 Propagation Loss

In practical photonic waveguides, the optical intensity decreases exponentially along the propagation direction due to several loss mechanisms. The total propagation loss $\alpha_{\text{total}} =$

$\alpha_{\text{abs}} + \alpha_{\text{scatt}} + \alpha_{\text{leak}}$ includes absorption loss, scattering loss, and substrate leakage, respectively.

For InGaAsP-on-insulator waveguides operating at 1550 nm, linear absorption loss is relatively small because the photon energy lies below the bandgap energy of the material. Consequently, the dominant propagation loss mechanism in sub-micron waveguides is side-wall scattering caused by fabrication-induced roughness.

The scattering loss scales approximately as:

$$\alpha_{\text{scatt}} \propto \frac{\langle \sigma^2 \rangle L_c}{\lambda^4} \left(\frac{n_{\text{core}}}{n_{\text{eff}}} \right)^4 \quad (1.12)$$

where σ is the RMS sidewall roughness amplitude and L_c is the correlation length. Minimising this loss through optimized lithography and ICP etching conditions is therefore critical for achieving efficient nonlinear waveguides.

1.3 Nonlinear Optics

This section introduces the nonlinear optical effects that are directly relevant to the work presented in this thesis. Specifically, four-wave mixing (FWM) is the primary nonlinear process investigated, forming the basis of the waveguide design presented in Chapter 4. Two-photon absorption (TPA) is also discussed as it represents an important limiting factor for nonlinear efficiency in InGaAsP waveguides.

1.3.1 Nonlinear polarization and Susceptibilities

When an optical field of sufficiently high intensity propagates through a dielectric medium, the induced polarization P can no longer be treated as a linear response to the electric field E [25]. The general constitutive relation is written as a power series in E :

$$P = \varepsilon_0 [\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \dots] \quad (1.13)$$

where $\chi^{(n)}$ is the n th-order nonlinear susceptibility tensor. The first-order term $\chi^{(1)}$ accounts for linear refraction and absorption. The second-order susceptibility $\chi^{(2)}$ is responsible for three-wave mixing processes and is non-zero only in non-centrosymmetric media. The third-order susceptibility $\chi^{(3)}$ mediates four-wave mixing and intensity-dependent phase effects, and is present in all materials.

InGaAsP belongs to the zinc-blende crystal class, which is non-centrosymmetric and therefore possesses a non-vanishing $\chi^{(2)}$ [26]. This distinguishes InGaAsP from silicon, which

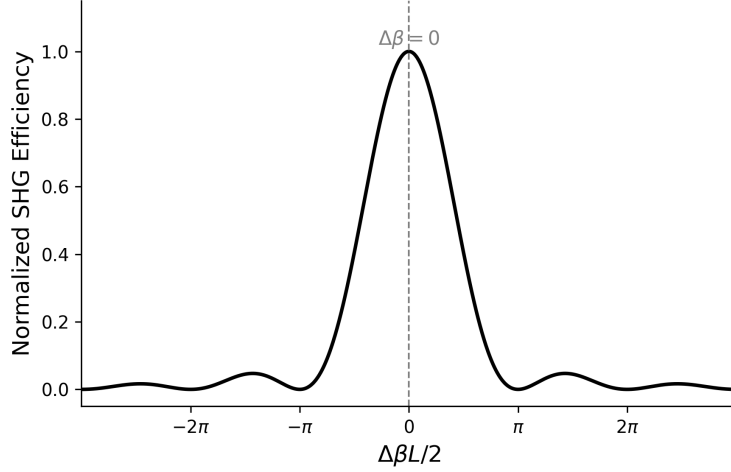


Figure 1.4: Typical $\text{sinc}^2(\Delta\beta L/2)$ phase-matching response illustrating the dependence of second-harmonic generation efficiency on phase mismatch. Maximum conversion efficiency occurs when $\Delta\beta = 0$ (adapted from Boyd, 2008).

has a centrosymmetric crystal structure and thus lacks an intrinsic bulk second-order nonlinear response.

1.3.2 Second-Order Nonlinear Effects

Second-order nonlinear processes arise from the interaction of three optical waves through $\chi^{(2)}$. Important second-order nonlinear effects include second-harmonic generation (SHG), sum-frequency generation (SFG), and difference-frequency generation (DFG).

In SHG, two photons at frequency ω interact to produce one photon at frequency 2ω . The nonlinear polarization at the second harmonic is given by:

$$P^{(2)}(2\omega) = \varepsilon_0 \chi^{(2)} : E(\omega)E(\omega) \quad (1.14)$$

The SHG conversion efficiency in a waveguide of length L is proportional to

$$\eta_{\text{SHG}} \propto |d_{\text{eff}}|^2 L^2 |I_{\text{overlap}}|^2 \text{sinc}^2\left(\frac{\Delta\beta L}{2}\right) \quad (1.15)$$

As illustrated in figure 1.5, second-harmonic generation occurs when two photons at frequency ω interact through the material $\chi^{(2)}$ nonlinearity to produce a photon at twice the optical frequency.

where d_{eff} is the effective nonlinear coefficient, I_{overlap} is the spatial mode overlap integral between the fundamental and second-harmonic modes, and

$$\Delta\beta = \beta(2\omega) - 2\beta(\omega) \quad (1.16)$$

is the phase mismatch. The dependence of the conversion efficiency on phase mismatch is illustrated in Figure 1.4, where the maximum nonlinear conversion occurs under perfect phase-matching conditions ($\Delta\beta = 0$).

Efficient conversion requires $|\Delta\beta| \approx 0$, which is achieved through phase-matching engineering [14]. Because material dispersion causes $n(2\omega) \neq n(\omega)$, phase matching generally requires modal phase matching, quasi-phase matching, or birefringence engineering. Modal phase matching exploits the geometry-dependent dispersion of different waveguide modes to equalize the effective indices at ω and 2ω . Quasi-phase matching uses periodic modulation of the nonlinear coefficient to compensate the accumulated phase mismatch over long interaction lengths, while birefringence phase matching exploits material anisotropy to match refractive indices at the interacting frequencies. Quasi-phase matching uses periodic modulation of the nonlinear coefficient, typically through domain inversion, to compensate the phase mismatch over long interaction lengths, as demonstrated in periodically-poled lithium niobate waveguides [27]. Birefringence phase matching exploits the natural anisotropy of the crystal to match refractive indices at the two frequencies [28].

In this thesis, modal phase matching is employed for SHG in InGaAsP-OI waveguides, exploiting the large second-order nonlinear coefficient of the zinc-blende InGaAsP crystal ($d_{14} \approx 100\text{--}200\text{ pm/V}$) without requiring any additional fabrication steps beyond the ridge waveguide geometry already needed for FWM; the design and analysis are presented in Chapter 5.

1.3.3 Third-Order Nonlinear Effects

Third-order effects arise from $\chi^{(3)}$ and include self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), third-harmonic generation (THG), and two-photon absorption (TPA).

Self-phase modulation produces an intensity-dependent phase shift given by

$$\phi_{\text{NL}} = \gamma PL, \quad (1.17)$$

where P is the optical power, L is the waveguide length, and γ is the nonlinear parameter defined as

$$\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}, \quad (1.18)$$

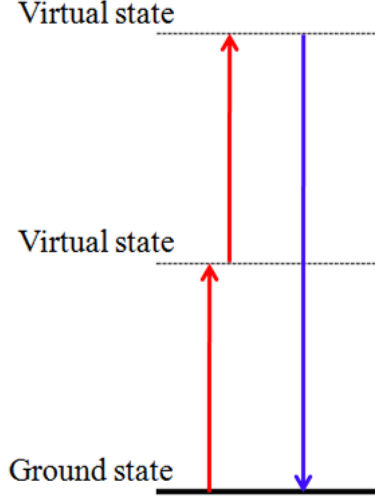


Figure 1.5: Energy-level representation of second-harmonic generation (SHG), where two photons at frequency ω combine to generate a photon at frequency 2ω through a second-order nonlinear interaction (adapted from [25]).

where n_2 is the nonlinear refractive index and A_{eff} is the effective mode area.

The effective mode area is given by

$$A_{\text{eff}} = \frac{(\iint |E|^2 dA)^2}{\iint |E|^4 dA}, \quad (1.19)$$

InGaAsP waveguides exhibit relatively large nonlinear parameters [23] due to their strong optical confinement and high nonlinear refractive index.

1.3.4 Four-Wave Mixing

Four-wave mixing (FWM) is a third-order nonlinear process in which optical energy is exchanged between multiple waves through the $\chi^{(3)}$ nonlinearity of the medium. The energy diagram for degenerate FWM is illustrated in Figure 1.7, where two pump photons at frequency ω_p are annihilated to generate a signal photon at ω_s and an idler photon at ω_i , as governed by energy conservation:

$$2\omega_p = \omega_s + \omega_i, \quad (1.20)$$

while momentum conservation requires minimization of the phase mismatch:

$$\Delta\beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p). \quad (1.21)$$

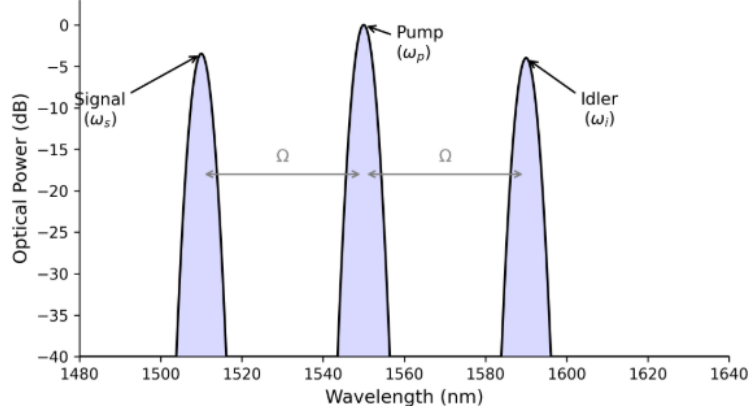


Figure 1.6: Typical four-wave mixing (FWM) optical spectrum illustrating the pump, signal, and idler peaks. In degenerate FWM, two pump photons at ω_p generate a signal at $\omega_s = \omega_p + \Omega$ and an idler at $\omega_i = \omega_p - \Omega$, symmetrically detuned by Ω from the pump wavelength.

Approximating the propagation constant expansion around the pump frequency gives:

$$\Delta\beta \approx \beta_2(\omega_s - \omega_p)^2 + \frac{1}{12}\beta_4(\omega_s - \omega_p)^4 + 2\gamma P, \quad (1.22)$$

where the final term accounts for nonlinear phase modulation effects.

For phase-matched FWM ($\Delta\beta \approx 0$), the parametric gain coefficient g quantifies the exponential growth rate of the signal and idler fields along the waveguide. It is given by:

$$g = \sqrt{(\gamma P)^2 - \left(\frac{\Delta\beta}{2}\right)^2} \quad (1.23)$$

Maximum gain occurs when $\Delta\beta = 0$, yielding:

$$g_{\max} = \gamma P \quad (1.24)$$

A typical FWM optical spectrum is illustrated in Figure 1.6, showing the pump, signal, and idler peaks symmetrically positioned around the pump wavelength ω_p .

Efficient FWM therefore strongly depends on dispersion engineering and operation near the zero-dispersion wavelength. As illustrated in Figure 1.7, degenerate four-wave mixing involves the interaction of two pump photons to generate signal and idler frequencies through the material third-order nonlinearity.

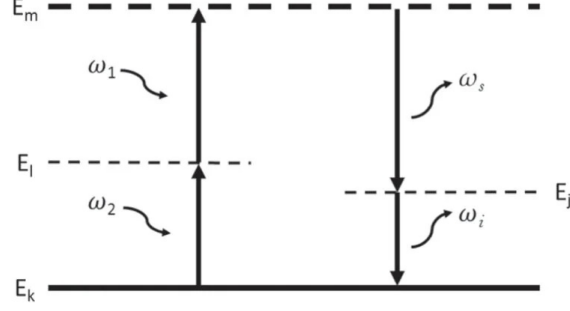


Figure 1.7: Energy diagram illustrating degenerate four-wave mixing (FWM), where two pump photons at frequency ω_p interact through the third-order nonlinearity $\chi^{(3)}$ to generate a signal photon at frequency ω_s and an idler photon at frequency ω_i (Boyd, 2008).

1.3.5 Two-Photon Absorption and Nonlinear Figure of Merit

An important parasitic effect in InGaAsP is two-photon absorption (TPA), which occurs when the photon energy exceeds half the material bandgap energy.

The TPA coefficient β_{TPA} contributes to nonlinear optical loss through the nonlinear absorption coefficient $\alpha = \alpha_0 + \beta_{\text{TPA}}I$, where α_0 is the linear absorption and I is the optical intensity, reducing the efficiency of nonlinear optical interactions.

The nonlinear figure of merit (FOM) is defined as:

$$\text{FOM} = \frac{n_2}{\lambda \beta_{\text{TPA}}} \quad (1.25)$$

For useful nonlinear optical interactions, the nonlinear figure of merit should generally satisfy:

$$\text{FOM} > \frac{1}{4\pi} \quad (1.26)$$

It is important to note that TPA cannot be completely eliminated in InGaAsP at telecommunications wavelengths due to the material bandgap. However, careful bandgap engineering through composition tuning can reduce β_{TPA} while preserving a large n_2 , improving the nonlinear figure of merit. As illustrated in Figure 1.8, two-photon absorption occurs when two photons are simultaneously absorbed to excite carriers across the material bandgap.

1.4 Comparison of Integrated Photonic Platforms

The choice of material platform is one of the most important decisions in the design of photonic integrated circuits [23]. Each platform exhibits different optical confinement, propagation loss, nonlinear response, active functionality, fabrication processes, and compatibility

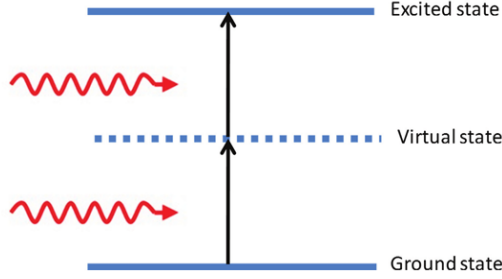


Figure 1.8: Schematic illustration of two-photon absorption (TPA), where two photons are simultaneously absorbed to excite an electron from the valence band to the conduction band [25].

with large-scale integration. As a result, no single material system can simultaneously satisfy all the requirements of modern integrated photonics, including efficient light emission, low-loss guiding, strong nonlinear response, high-speed modulation, detection, scalability, and low-cost fabrication. This has motivated the development of heterogeneous photonic platforms, where different materials are integrated on a common substrate to combine their complementary advantages.

Silicon-on-insulator (SOI) is one of the most mature and widely used platforms for integrated photonics [9]. Its high refractive index contrast enables compact waveguides, small bending radii, and dense photonic circuits. In addition, the compatibility of silicon processing with CMOS fabrication makes SOI attractive for scalable manufacturing. However, silicon has an indirect bandgap and therefore cannot efficiently emit light [9]. It also lacks intrinsic second-order nonlinearity because of its centrosymmetric crystal structure. Furthermore, at telecommunication wavelengths, silicon suffers from two-photon absorption and free-carrier absorption under high optical intensities, which limits its performance for nonlinear optical applications.

Silicon nitride (Si_3N_4) is another important platform, especially for low-loss passive photonics and frequency-comb generation [8]. It exhibits a wide transparency window, negligible two-photon absorption at telecommunication wavelengths, and very low propagation loss. However, its nonlinear refractive index is lower than that of silicon and III–V semiconductors, and it does not provide native active functionality such as optical gain or efficient photodetection [8].

Lithium niobate (LiNbO_3) has attracted significant attention because of its strong electro-optic effect and second-order nonlinearity [19]. Thin-film lithium-niobate-on-insulator platforms enable high-speed modulators and efficient nonlinear frequency conversion. Nevertheless, lithium niobate does not provide efficient light emission or detection, and its fabrication and heterogeneous integration remain more complex than standard silicon photonics [29].

Table 1.1: Comparison of selected integrated photonic platforms near telecommunication wavelengths. Values are representative and may vary depending on wavelength, material composition, and fabrication process.

Platform	n at 1550 nm	n_2 ($\times 10^{-18}$ m ² /W)	Loss (dB/cm)	CMOS Compatible	Native Gain	Key Limitation
SOI	~ 3.48	~ 0.45	0.5–3	Yes	No	TPA; no intrinsic $\chi^{(2)}$
Si ₃ N ₄	~ 2.00	~ 0.025	0.01–0.1	Yes	No	Weak nonlinearity; no optical gain
LiNbO ₃ -OI	~ 2.21	~ 0.03	0.02–0.3	Partial	No	Complex etching; no light emission
AlGaAs-OI	~ 3.30	~ 100 –260	1–3	No	Yes	Fabrication complexity; heterogeneous integration
InGaAsP-OI	~ 3.35	~ 10	1–5	No	Yes	Bonding yield; delamination; TPA at 1550 nm

III–V compound semiconductors, including InP, GaAs, AlGaAs, and InGaAsP, offer several advantages that are not available in purely silicon-based platforms [7]. Their direct bandgap enables efficient light emission, optical amplification, and detection. In addition, many III–V materials possess strong second- and third-order nonlinearities, making them attractive for nonlinear photonic applications. InGaAsP is particularly important because its bandgap can be engineered for operation near telecommunication wavelengths, making it suitable for active devices and nonlinear waveguides operating around 1.55 μm [30].

However, conventional III–V photonic platforms grown on native substrates often have lower vertical index contrast than insulator-based platforms, which limits optical confinement and increases device footprint [6]. III–V-on-insulator platforms address this limitation by transferring thin III–V layers onto low-index oxide substrates. This approach combines the strong optical properties of III–V semiconductors with the high confinement of an insulator platform [30]. The success of AlGaAs-on-insulator for nonlinear photonics motivates the development of InGaAsP-on-insulator as a promising platform for nonlinear photonic applications. Table 1.1 provides a comparison of common integrated photonic platforms. Table 1.2 compares the nonlinear optical parameters, including n_2 , β_{TPA} , γ , and FOM of selected integrated photonic materials near telecommunication wavelengths. Values are approximate and depend on wavelength, material composition, and fabrication conditions.

A more quantitative comparison of nonlinear properties is shown in Table 1.2. Silicon has a large nonlinear refractive index, but its nonlinear performance at telecommunication wavelengths is limited by two-photon absorption. In contrast, materials such as Si₃N₄, Hydex, and Ta₂O₅ exhibit negligible two-photon absorption but have lower nonlinear refractive indices. III–V semiconductors can provide strong nonlinearities together with active functionality, making them especially attractive for compact nonlinear photonic circuits.

Table 1.1 summarizes the relevance of each platform to the objectives of this thesis. While silicon and silicon nitride are highly mature, they lack native active functionality. Lithium niobate is excellent for electro-optic modulation and second-order nonlinear optics, but it does not provide gain. III–V-on-insulator platforms are therefore especially attractive because they combine strong confinement with the active and nonlinear properties of III–V

Table 1.2: Comparison of nonlinear optical properties of selected integrated photonic platforms. The nonlinear parameter γ depends on wavelength and waveguide geometry.

Material	n_2 (m ² /W)	β_{TPA} (cm/GW)	γ (W ⁻¹ m ⁻¹)	FOM = $n_2/(\lambda\beta_{\text{TPA}})$	Notes / References
SiO ₂ fibre	$\sim 2.6 \times 10^{-20}$	Negligible	~ 0.001	N/A	Reference baseline; low nonlinearity
Si ₃ N ₄	$\sim 2.5 \times 10^{-19}$	Negligible	~ 1	N/A	Low loss; used for frequency combs
Si (SOI)	$\sim 6 \times 10^{-18}$	~ 0.5	~ 200	~ 0.39	Limited by TPA and free-carrier absorption at 1550 nm
AlGaAs-OI	$\sim 2.6 \times 10^{-17}$	~ 0.04	~ 600	~ 1.7	Strong $\chi^{(2)}$ and $\chi^{(3)}$ nonlinearities
InGaAsP-OI	$\sim 1 \times 10^{-17}$	~ 15	$\sim 36.85^\dagger$	~ 0.43	† Estimated for a $0.8 \mu\text{m} \times 0.8 \mu\text{m}$ waveguide

semiconductors. This motivates the investigation of InGaAsP-on-insulator as a platform for nonlinear photonic applications.

Overall, the comparison shows that InGaAsP-on-insulator occupies a distinctive position among integrated photonic platforms. Compared with mature passive platforms such as SiN and LiNbO₃, InGaAsP-OI offers stronger nonlinear response and the possibility of active functionality due to its direct bandgap. Compared with silicon, its quaternary alloy composition allows bandgap engineering to reduce two-photon absorption near telecommunication wavelengths while preserving a large Kerr nonlinearity. At the same time, the platform remains less mature than established SOI and SiN technologies because bonding quality, substrate removal, surface roughness, and delamination remain important fabrication challenges. These advantages and limitations motivate the bonding and fabrication studies discussed in the following chapters. Its main promise lies in combining telecommunication-band operation, direct-bandgap functionality, strong optical confinement, and nonlinear optical response. At the same time, the platform introduces important fabrication challenges, particularly bonding quality, substrate removal, surface roughness, and delamination. These challenges motivate the bonding and fabrication studies discussed in the following chapters.

1.5 Fabrication of III–V Photonic Devices

The realisation of III–V photonic integrated circuits requires the orchestration of several advanced process modules: epitaxial crystal growth, lithographic patterning, pattern transfer by etching, and heterogeneous integration onto foreign substrates. Unlike silicon microelectronics, where a largely unified CMOS platform has dominated for decades, III–V photonics has developed through a heterogeneous paradigm in which no single material system simultaneously satisfies all requirements, efficient light generation, low-loss waveguiding, strong optical nonlinearity, high-speed modulation, and scalable manufacturability [31, 32]. The following subsections describe each fabrication step in detail, compare competing techniques, and identify the process requirements most critical for the InGaAsP-on-insulator (InGaAsP-OI) nonlinear waveguide platform developed in this thesis.

1.5.1 Epitaxial Growth

The starting point for every III–V photonic device is the controlled deposition of a crystalline semiconductor heterostructure on a lattice-matched substrate, a process termed *epitaxy* (from the Greek *epi*, upon, and *taxis*, arrangement). Epitaxial growth defines the waveguide core, optical confinement layers, quantum-well gain regions, etch-stop markers, and sacrificial substrates that collectively determine device performance. Precise control of layer thickness (often to within a few atomic monolayers ≈ 0.3 nm), alloy composition, doping profile, and interface abruptness is therefore indispensable [11].

For InGaAsP-OI platforms, epitaxial growth is performed by MOCVD on InP substrates. The resulting heterostack comprising an InP buffer, the InGaAsP waveguide core, and an InP capping layer, which is subsequently bonded face-down onto the SiO₂/Si handle wafer. Precise core thickness is critical because group velocity dispersion and the zero-dispersion wavelength (ZDW) are sensitive functions of waveguide dimensions: a ± 10 nanometers variation in core thickness shifts the ZDW by several tens of nanometres, which can substantially degrade FWM phase-matching efficiency (see Chapter 4).

Metal-Organic Chemical Vapour Deposition (MOCVD)

Metal-organic chemical vapour deposition (MOCVD), also called metal-organic vapour-phase epitaxy (MOVPE), is the dominant industrial technique for III–V epitaxy [33]. In MOCVD, volatile metal-organic precursors are introduced into a reactor chamber where they undergo pyrolytic decomposition on a heated susceptor. For InGaAsP on InP, the standard precursors are trimethylindium (TMIn), trimethylgallium (TMGa), arsine (AsH₃), and phosphine (PH₃). The group-V/III ratio, partial pressures, carrier gas (typically H₂ or N₂), reactor pressure, and substrate temperature ranging 550 °C to 750 °C for InP-based materials) are adjusted to control layer composition, growth rate, and surface morphology [34].

Key advantages of MOCVD include compatibility with selective-area growth (SiO₂ or Si₃N₄ masks locally suppress deposition, enabling multiple bandgap devices on a single wafer), multi-wafer batch capability, and the high-volume reproducibility required for telecommunication laser production.

Molecular Beam Epitaxy (MBE)

Molecular beam epitaxy (MBE) operates under ultra-high vacuum (UHV, $\sim 10^{-10}$ Torr), where thermally evaporated atomic beams impinge on a heated substrate. Source materials are evaporated from Knudsen effusion cells with mechanical shutters that control each element independently with monolayer-level precision. Because MBE is a physical rather than

Table 1.3: Comparison of MOCVD and MBE epitaxial growth techniques for III–V photonic device fabrication. Values are representative; exact conditions depend on material system and reactor design [36].

Parameter	MOCVD / MOVPE	MBE
Operating pressure	10–760 Torr	$\sim 10^{-10}$ Torr (UHV)
Growth temperature (InP)	550 °C to 750 °C	480 °C to 650 °C
Interface abruptness	~ 1 –2 monolayers	< 1 monolayer
Composition control	Precursor partial pressures	Shutter timing / cell T
Throughput	High (multi-wafer batch)	Low (single wafer)
In-situ monitoring	Optical reflectometry	RHEED
Selective-area growth	Yes (SiO ₂ mask)	Limited
Toxic hazards	Hydride gases (AsH ₃ , PH ₃)	Solid sources (lower acute risk)
Industrial maturity	Very high	Moderate
Primary application	Telecom lasers, PICs	Research, quantum structures

chemical deposition process, it produces extremely abrupt heterointerfaces (< 1 monolayer) and precise doping profiles [35]. In-situ reflection high-energy electron diffraction (RHEED) provides real-time feedback on surface crystallography and growth rate.

MBE is the preferred technique for structures demanding atomic-scale control such as single quantum dots, dilute nitrides, strained superlattices, but its low throughput (single wafer), sensitivity to vacuum excursions, and high equipment cost restrict its use to research and specialised production.

Comparison of MOCVD and MBE

Table 1.3 summarises the principal characteristics of MOCVD and MBE for III–V photonic applications. For InGaAsP-OI waveguides, MOCVD on InP is the standard approach because it provides the uniformity, throughput, and multi-layer capability required for the heterostack described above.

1.5.2 Lithographic Patterning

After bonding and substrate removal, the waveguide geometry must be transferred into the InGaAsP layer. This is accomplished through a lithographic process in which a radiation-sensitive polymer film (the *resist*) is exposed to define a mask pattern that is subsequently transferred into the semiconductor by etching. The lithographic step is the primary determinant of waveguide critical dimension (CD) accuracy; in nonlinear photonic devices a width variation of only ± 50 nm can shift the ZDW by ~ 30 nm and substantially degrade

phase-matching.

Photoresists: Chemistry and Tone

A *photoresist* is a radiation-sensitive polymer dissolved in a casting solvent and deposited by spin-coating. Film thickness (typically 100 nm to 3000 nm) is set by spin speed and solution viscosity. After spin-coating, a *soft bake* at 90 °C to 120 °C drives off residual solvent and densifies the film. Resists are classified by their *tone*:

Positive-tone resists. Exposure to radiation causes main-chain scission in the polymer backbone, reducing molecular weight and rendering exposed regions soluble in an aqueous alkaline developer (typically 2.38 % tetramethylammonium hydroxide, TMAH). The developed image therefore replicates the *clear* (transparent) features of a photomask, the exposed material is removed and the unexposed regions remain as the etch mask. Representative examples:

- **S1800 series** (Shipley/Dow): workhorse i-line optical resist; 1 μm to 10 μm features.
- **PMMA** (poly(methyl methacrylate)): standard positive e-beam resist; resolution < 10 nm in high-MW formulations; limited etch resistance.
- **ZEP520A** (Zeon Corp.): positive e-beam resist with $\sim 3\times$ higher etch resistance than PMMA and improved sensitivity; widely used for III–V waveguide masks.

Negative-tone resists. Exposure initiates photo- or radiation-induced cross-linking, rendering the exposed regions insoluble. An organic solvent developer removes the unexposed regions, leaving cross-linked exposed material as the mask. The developed image is therefore the *complement* of the mask openings. Representative examples:

- **SU-8** (MicroChem): epoxy-based negative resist for optical/DUV lithography; excellent for thick ($> 1 \mu\text{m}$) high-aspect-ratio structures; very high etch resistance.
- **ma-N 2400 series** (micro resist technology): negative-tone e-beam resist; higher sensitivity than HSQ; suitable for dense sub-micron patterns.
- **HSQ** (hydrogen silsesquioxane): negative-tone e-beam resist that converts to an amorphous SiO_2 -like matrix upon exposure; resolution < 10 nm, very high etch resistance, but low sensitivity ($> 1 \text{ mC cm}^{-2}$).

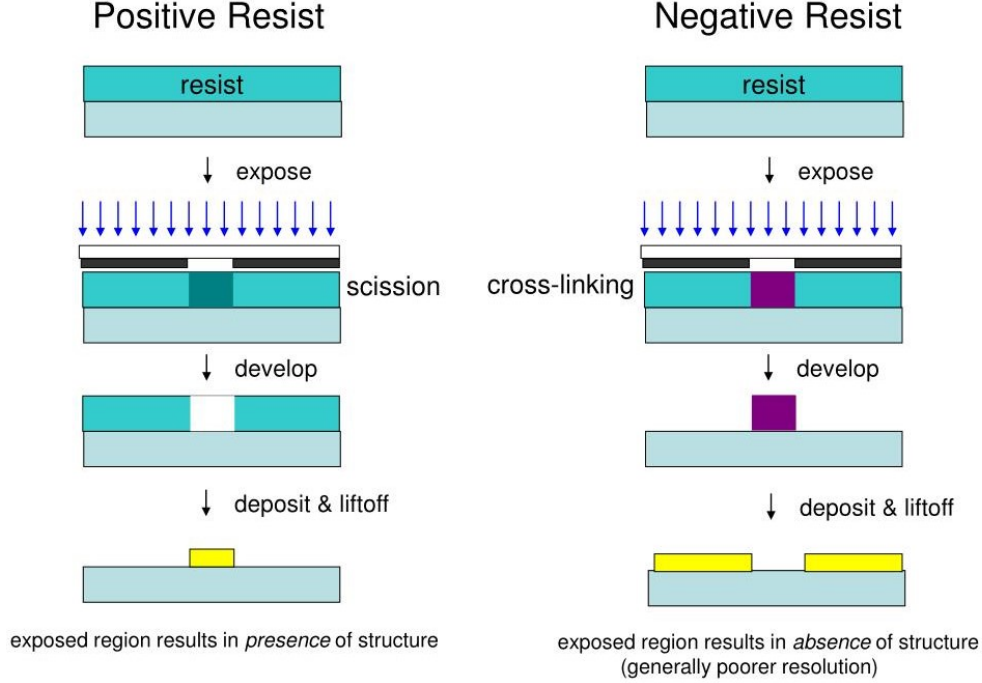


Figure 1.9: Schematic comparison of positive-tone and negative-tone photoresist processes. **Left (positive):** The exposed region undergoes chain scission, reducing the molecular weight of the polymer and rendering it soluble in developer; after development, the exposed region is removed, leaving a gap in the resist. Subsequent material deposition and lift-off result in a deposited feature at the location of the original opening, so the exposed region corresponds to the *presence* of the final structure. **Right (negative):** The exposed region undergoes cross-linking and becomes insoluble; development removes the unexposed resist, leaving the cross-linked material. After deposition and lift-off, the final structure is present everywhere *except* at the exposed site, so the exposed region corresponds to the *absence* of the final structure. Negative-tone resists generally produce lower resolution than positive-tone resists due to swelling of the cross-linked network during development [37].

The choice of tone affects lift-off vs. etch-mask compatibility, pattern density, and sidewall profile. For sub-micron waveguide patterning by EBL, ZEP520A (positive) offers the best balance of resolution, sensitivity, and etch resistance for InGaAsP-OI; HSQ is preferred when maximum etch resistance is required. A comparison of the positive-tone and negative-tone resist processes is shown in Figure 1.9.

Optical Photolithography

In optical (UV) photolithography, the resist is exposed through a chrome-on-glass photomask using a UV lamp (436 nm g-line, 365 nm i-line) or a deep-UV (DUV) excimer laser source (248 nm KrF or 193 nm ArF). Three exposure modalities are used in practice: Con-

tact/proximity printing places the mask either in direct contact with or in very close proximity (typically a gap of about $5\mu\text{m}$) to the photoresist. While this approach is simple and widely used for non-critical patterning steps in research, its resolution is fundamentally limited by diffraction to roughly $1\mu\text{m}$, and repeated contact also leads to progressive mask degradation. In projection (reduction) lithography, by contrast, a lens system projects a reduced image of the mask onto the wafer, typically with demagnification factors of 4:1 or 5:1. Modern step-and-scan systems using deep-UV (DUV) sources achieve critical dimensions on the order of 90 nm in high-volume manufacturing and form the backbone of silicon photonic foundries. An extension of this approach is immersion lithography, where the gap between the final lens and the wafer is filled with de-ionised water (refractive index $n \approx 1.44$), effectively increasing the numerical aperture and enabling feature sizes below 40 nm when combined with phase-shift masks and optical proximity correction (OPC).

The minimum resolvable feature in projection lithography is governed by the Rayleigh criterion:

$$CD_{\min} = k_1 \frac{\lambda}{\text{NA}} \quad (1.27)$$

where k_1 is a process-dependent factor (typically 0.4–0.8), λ is the exposure wavelength, and NA is the numerical aperture of the projection lens. For i-line lithography ($\lambda = 365\text{ nm}$, $\text{NA} = 0.65$), $CD_{\min} \approx 280\text{ nm}$, which is insufficient for sub-micron III–V waveguide cores. DUV scanners extend this but remain expensive and require mask sets, making optical lithography most appropriate for larger features ($>1\mu\text{m}$) or wafer-scale production.

Electron-Beam Lithography (EBL)

Electron-beam lithography (EBL) uses a focused beam of electrons (typically 10 keV to 100 keV) to directly write patterns in an electron-sensitive resist without a physical mask. Because the de Broglie wavelength of electrons at 100 keV is $\approx 0.004\text{ nm}$, many orders of magnitude shorter than UV wavelengths, EBL resolution is not limited by optical diffraction but by:

- **Forward scattering** of the primary beam in the resist ($\propto$ resist thickness / beam energy);
- **Backscattering** of electrons from the substrate, which deposits energy at distances of several micrometres from the primary exposure site (*proximity effect*).

The proximity effect can be corrected computationally by modulating the exposure dose across the pattern, a process known as proximity effect correction (PEC) [38]. With PEC

Table 1.4: Comparison of optical photolithography and electron-beam lithography (EBL) for III–V photonic nanofabrication [23].

Parameter	Optical lithography	EBL
Minimum feature size	$\sim 1\ \mu\text{m}$ (i-line); $\sim 90\ \text{nm}$ (DUV scanner)	$< 10\ \text{nm}$
Physical mask required	Yes (chrome-on-glass)	No (direct-write)
Throughput	Very high (wafer/min)	Very low (cm^2/hour)
Overlay accuracy	5–20 nm (scanner)	3–10 nm
Proximity / diffraction effect	Diffraction (corrected by OPC)	Proximity effect (corrected by PEC)
Typical resists	S1800, SPR, SU-8 (negative)	PMMA, ZEP520A (positive); HSQ, ma-N (negative)
Capital cost	Low (contact); very high (DUV scanner)	Very high
Best application	Production; features $> 500\ \text{nm}$	Research; sub-500 nm features

and optimised development, EBL routinely achieves feature sizes of 20 nm in research environments, and sub-10 nm with specialist resists and low-voltage beams.

EBL is the standard patterning technique for sub-micron III–V waveguide cross-sections, photonic crystal structures, and grating couplers in research and prototyping. Its chief limitation is low throughput: writing is serial and a $1\ \text{cm}^2$ field at typical doses takes minutes to hours, restricting EBL to small-area, high-value devices. Multi-beam EBL tools improve throughput but remain expensive. Figure 1.10 illustrates the EBL column architecture (a), the proximity effect and double-Gaussian energy deposition profile (b), and SEM cross-sections comparing waveguide sidewall quality under non-optimised and optimised etch conditions (c). Table 1.4 compares the two techniques across parameters relevant to III–V nanophotonic fabrication.

1.5.3 Etching Techniques

After lithographic patterning, the resist mask defines the waveguide geometry, which must be transferred vertically into the semiconductor with high dimensional fidelity. Two broad etching classes are employed in III–V photonic fabrication: *wet chemical etching* and *dry (plasma) etching*. Each offers distinct trade-offs in selectivity, profile anisotropy, surface quality, and process control.

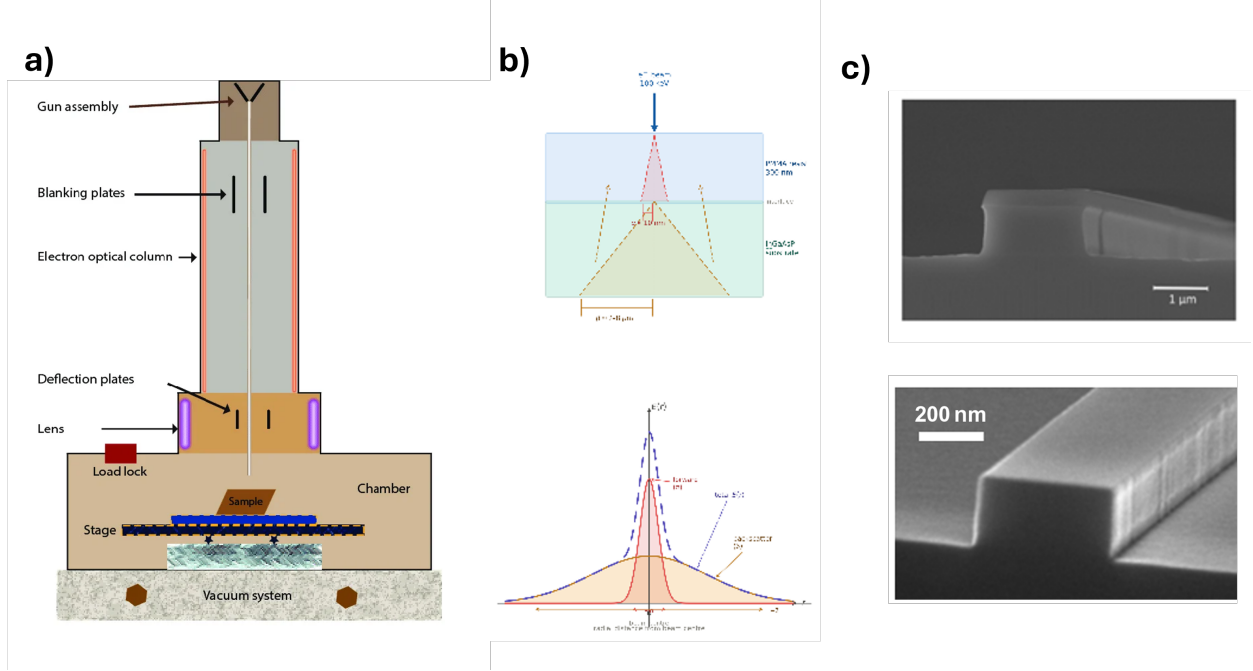


Figure 1.10: Electron-beam lithography (EBL): system, proximity effect, and waveguide performance. **(a)** Schematic of an EBL system showing the gun assembly, blanking plates, electron optical column, deflection plates, objective lens, load lock, sample stage, and vacuum system [39]. **(b)** *Top*: forward and backscattering trajectories of a 100 keV electron beam in a 300 nm PMMA resist film on an InGaAsP substrate. Forward scattering (red, radius $\alpha \approx 10$ nm) is confined within the resist and governs the intrinsic beam resolution. Backscattering (orange, radius $\beta \approx 2\text{--}8\text{ }\mu\text{m}$) originates from electrons returning from the substrate into the resist at large lateral distances, giving rise to the *proximity effect* [40]. *Bottom*: the resulting double-Gaussian energy deposition profile $E(r)$, comprising a narrow forward peak and a broad backscatter pedestal whose sum (blue dashed) defines the total exposure at each radial distance from the beam centre [41]. **(c)** SEM cross-sections of InGaAsP/InP ridge waveguides etched by ICP-RIE. *Top*: waveguide showing tapered sidewalls resulting from non-optimised etch conditions, with a 1 μm scale bar. *Bottom*: waveguide with near-vertical sidewalls and reduced line-edge roughness achieved through optimised lithography and etch parameters, with a 200 nm scale bar. Both SEM images adapted from [42].

Wet Chemical Etching

Wet etching dissolves the target semiconductor in a liquid etchant through oxidation–reduction reactions at the semiconductor surface. Three parameters govern performance:

- **Etch rate:** controlled by solution concentration, temperature, and agitation.
- **Selectivity** $S = R_{\text{target}}/R_{\text{stop}}$: the ratio of etch rates between the target material and a stop or masking layer (Equation 1.28). High selectivity is exploited for substrate removal and sacrificial-layer release.
- **Profile isotropy:** wet etchants are generally isotropic in amorphous materials (equal rate in all directions), producing lateral undercut beneath the mask that limits achievable linewidth and aspect ratio. Crystallographically selective etchants can produce faceted profiles in III–V single crystals.

$$S = \frac{R_{\text{target}}}{R_{\text{mask or stop}}} \quad (1.28)$$

Commonly used wet etchants for InP- and InGaAsP-based III–V structures are summarised in Table 1.5. The high selectivity of HCl:H₂O (3:1) for InP over InGaAs/InGaAsP is the basis of the substrate removal process used in this work, where the InGaAs etch-stop layer provides a sharp chemical endpoint. The citric acid:H₂O₂ system provides complementary selectivity for subsequent InGaAs removal, stopping cleanly on the InGaAsP waveguide core.

Although wet etching provides high selectivity and avoids plasma-induced crystalline damage, its isotropic nature makes it unsuitable for defining sub-micron waveguide geometries because lateral undercut degrades sidewall verticality and pattern fidelity. Wet etching is therefore used exclusively for substrate removal and sacrificial-layer release in InGaAsP-OI fabrication.

Reactive Ion Etching (RIE)

Reactive ion etching (RIE) uses a plasma generated by an RF-driven parallel-plate reactor to produce reactive radicals and energetic ions that simultaneously attack the target material chemically and physically. The DC self-bias of the powered electrode accelerates positive ions toward the substrate, providing directionality and enabling more anisotropic profiles than wet etching. However, standard RIE couples plasma density and ion energy through a single RF source, limiting the independent optimisation of etch rate, selectivity, and profile.

Table 1.5: Common wet chemical etchants used for InP- and InGaAsP-based III–V semiconductor structures. Etch rates and selectivity values are representative and depend on material composition, temperature, and solution concentration.

Etchant	Target	Selective to	$S = R_{\text{target}}/R_{\text{stop}}$	Notes
HCl:H ₂ O (3:1), 20 °C	InP	InGaAs / In-GaAsP	$S > 100$	$R_{\text{InP}} \approx 3\text{--}5 \mu\text{m}/\text{min}$; InGaAs/InGaAsP etch rate negligible [43]
H ₃ PO ₄ :HCl (3:1), 20 °C	InP	InGaAsP	$S \approx 10\text{--}30$	$R_{\text{InP}} \approx 1 \mu\text{m}/\text{min}$; smooth surface [43]
Citric acid:H ₂ O ₂ (4:1–50:1), 21 °C	InGaAs / In-GaAsP	InP	$S \approx 60\text{--}120$	$R_{\text{InGaAs}} \approx 0.1\text{--}0.3 \mu\text{m}/\text{min}$ at 4:1; ratio-dependent [44]
H ₂ SO ₄ :H ₂ O ₂ :H ₂ O (1:1:10), 21 °C	InGaAs / In-GaAsP	InP	$S \approx 30\text{--}70$	$R_{\text{InGaAsP}} \approx 0.10 \mu\text{m}/\text{min}$; smooth morphology [43]
HCl:HF:CrO ₃ (x :0.5:1)	InGaAs	InGaAsP	$S = 1.5\text{--}42.4$	Decreases with increasing x ; tunable taper angles [45]
HCl:HNO ₃ :H ₂ O (2:2:1), 25 °C	AlInP / Al-GaP	GaAs	Composition-dep.	$R_{\text{InP}} \approx 2 \mu\text{m}/\text{min}$; non-selective regime [43]
HCl:H ₂ O ₂ :H ₂ O (1:1:10)	GaAs	GaAsP	Composition-dep.	Selective and non-selective modes depending on ratio [43]

Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE)

ICP-RIE is the preferred technique for high-index-contrast III–V nanophotonic devices [46]. An inductively coupled RF coil external to the chamber generates a high-density plasma ($n_e \sim 10^{11}\text{--}10^{12}\text{ cm}^{-3}$) independently of the substrate bias. A separate RF source on the substrate platen controls the DC self-bias and thus the ion energy incident on the wafer surface. This decoupling of plasma density and ion energy allows the etch rate, sidewall angle, and surface damage to be controlled independently and precisely. The etch rate is governed primarily by the plasma density and radical flux, while the sidewall angle is determined by the relative contributions of chemical and physical etch components. Surface damage and mask erosion, by contrast, are controlled through the ion energy at the substrate surface, which can be adjusted via the RF bias power without affecting the plasma density.

For InGaAsP and InP, chlorine-based plasma chemistries are most widely used. Cl_2/Ar mixtures provide high etch rates with good anisotropy: chlorine radicals react with In, Ga, and P to form volatile chloride by-products (InCl_3 , GaCl_3 , PCl_3), while Ar ions sputter away involatile surface species that would otherwise passivate the surface and arrest etching. The addition of CH_4 or H_2 can passivate sidewalls and suppress lateral etching, trading etch rate for improved profile verticality.

Sidewall roughness introduced during ICP-RIE is the dominant source of propagation loss in sub-micron InGaAsP-OI waveguides. Scattering loss scales as $\sigma^2 L_c / \lambda^4$ (where σ is the RMS roughness amplitude and L_c is the correlation length), so minimising roughness through optimised resist quality, low RF-bias conditions, and controlled plasma chemistry is critical for achieving low-loss nonlinear waveguides.

Focused Ion Beam (FIB) Milling

Focused ion beam (FIB) milling uses a focused Ga^+ or Xe^+ beam to physically sputter material with nanometre-scale precision. In photonic fabrication, FIB is used in III–V photonic fabrication primarily for end-facet preparation and spot-size converter definition, for post-process trimming of waveguide dimensions to correct lithographic errors, and for cross-sectional sample preparation for SEM and TEM characterization. FIB is a slow serial process and introduces Ga^+ implantation damage and surface amorphisation, making it unsuitable for large-area patterning but valuable for prototyping and failure analysis.

Comparison of Etching Techniques

Table 1.6 summarises wet etching, RIE, ICP-RIE, and FIB milling across parameters relevant to III–V photonic fabrication.

Table 1.6: Comparison of etching techniques used in III–V photonic device fabrication for InP- and InGaAsP-based platforms. Performance metrics depend on material system, etchant chemistry, and process conditions.

Parameter	Wet etching	RIE	ICP-RIE	FIB milling
Typical etch rate (InP)	$1\text{ }\mu\text{m min}^{-1}$ to $5\text{ }\mu\text{m min}^{-1}$ (e.g. HCl:H ₂ O 3:1) [43]	$\sim 45\text{ nm min}^{-1}$ (Cl ₂ /Ar, standard RIE) [47]	900 nm min^{-1} to 2000 nm min^{-1} (Cl ₂ /H ₂ /Ar) [48, 46]	10 nm min^{-1} to 100 nm min^{-1} (30 kV Ga ⁺ , material-dependent) [49]
Mask-to-semiconductor selectivity	$S \gg 100$ (chemically selective stop layers, e.g. HCl:H ₂ O on InP/InGaAs) [43]	$S \approx 3\text{--}8$ (photore-sist mask)	$S \approx 9\text{--}30$ (SiO ₂ or SiN _x mask) [48, 46, 50]	$S < 2$ (physi-cal sputtering, no chemical selectiv-ity) [49]
Sidewall angle	$\sim 54^\circ\text{--}70^\circ$ (crys-tallographic or isotropic undercut)	$70^\circ\text{--}80^\circ$ (limited anisotropy) [47]	$86^\circ\text{--}89.5^\circ$ (Cl ₂ /H ₂ /Ar, optimised) [48, 50]	$\geq 85^\circ$ (physical milling, beam-angle depen-dent) [49]
Sidewall RMS roughness	$> 20\text{ nm}$ (isotropic dissolution and un-dercut)	$5\text{--}15\text{ nm}$ (limited ion directional control)	$2\text{--}6\text{ nm}$ (Cl ₂ /Ar/H ₂ , optimised) [51]	$5\text{--}30\text{ nm}$ (redeposi-tion and Ga ⁺ dam-age) [49]
Plasma-induced damage depth	None	$5\text{--}20\text{ nm}$ (ion bom-bardment)	$2\text{--}10\text{ nm}$ (low bias; less than RIE at equivalent rate)	$10\text{--}30\text{ nm}$ (Ga ⁺ im-plant zone) [49]
Minimum feature size	$1\text{ }\mu\text{m}$ (lateral un-dercut limits reso-lution)	$200\text{--}500\text{ nm}$ (lim-ited profile control)	$< 100\text{ nm}$ (sub-micron waveguides demonstrated) [48]	$< 10\text{ nm}$ (7 nm beam spot at 30 kV) [52]
Throughput	Batch process; $1\text{ }\mu\text{m min}^{-1}$ to $10\text{ }\mu\text{m min}^{-1}$, wafer-scale	Single wafer; 45 nm min^{-1} , slow for deep etches	Single wafer; $0.9\text{ }\mu\text{m min}^{-1}$ to $2\text{ }\mu\text{m min}^{-1}$, suitable for device-scale	Serial point-by-point; $\sim 30\text{ s}$ per facet at 15 nA [53]
Primary appli-cation in III–V photonics	Substrate removal; etch-stop release	Shallow mesa ($< 2\text{ }\mu\text{m}$) structures	Nanophotonic waveguides; deep ridge etching	Facet preparation; TEM cross-section; post-process trim

Despite its advantages, BCB bonding introduces fabrication challenges that are analysed in detail in Chapter 3: void formation at the BCB/SiO₂ interface, delamination driven by thermal stress during InP substrate removal, and wet-etch-induced surface roughness on the exposed InGaAsP core. Table 2.2 compares the three main heterogeneous integration techniques. BCB bonding is selected for this work because it combines a low process temperature with high tolerance to surface roughness, both critical given the morphological challenges encountered during InP substrate removal.

1.5.4 Surface and Structural characterization

Throughout the fabrication sequence, the structural quality, surface morphology, and composition of the layers are monitored by a suite of complementary characterization techniques. Field-emission SEM (FE-SEM) provides sub-5 nm resolution imaging of waveguide cross-sections, etch profiles, and sidewall morphology, and serves as the primary tool for verifying etch depth, sidewall angle, and layer thicknesses after bonding. Surface roughness is quantified by tapping-mode AFM, which measures the RMS roughness R_q and autocorrelation length L_c over typically $5\text{ }\mu\text{m}\times 5\text{ }\mu\text{m}$ scan areas; since these parameters enter directly into the sidewall scattering loss model, AFM measurements are performed after each wet etching step as a critical process control metric. Elemental composition mapping is carried out by energy-dispersive X-ray spectroscopy (EDX) performed within the SEM on cross-sectional samples, providing verification of the InGaAsP alloy composition and confirmation of complete InP substrate removal following the selective wet etch sequence.

1.5.5 Wafer Bonding for III–V-on-Insulator

Because direct monolithic growth of III–V semiconductors on silicon is severely limited by lattice mismatch ($\sim 8\%$ for InP/Si), thermal expansion mismatch, and antiphase domain formation [59], high-quality InGaAsP layers cannot be grown directly on SiO₂/Si substrates without introducing threading dislocations and crystalline defects that degrade optical performance. Heterogeneous integration, in which a III–V epitaxial layer is grown on a native InP substrate and subsequently transferred onto a pre-fabricated SiO₂/Si handle wafer, therefore provides the only practical route to InGaAsP-on-insulator photonic platforms. Three bonding approaches are established in the literature for this purpose: direct (molecular) wafer bonding, in which two chemically activated surfaces are annealed to form covalent Si–O–Si bonds; plasma-activated bonding, a variant that reduces the required anneal temperature to 150 °C to 300 °C through O₂ or N₂ plasma surface treatment; and adhesive bonding using benzocyclobutene (BCB), which employs a spin-coated polymer interlayer

Table 1.7: Comparison of heterogeneous integration bonding techniques for III–V-on-insulator photonic platforms. Values are representative and depend on surface preparation, anneal conditions, and material system.

Parameter	Direct (molecular) bonding	Plasma-activated bonding	BCB adhesive bonding
Bonding / anneal temperature	600 °C to 1000 °C for full covalent strength; Si–Si bond completion at ~ 700 °C [54]	150 °C to 350 °C; $\gamma \approx 1.76 \text{ J m}^{-2}$ achieved at 350 °C anneal [55]	250 °C full cure, 1 h in N_2 ; pre-cure at 210 °C [56]
Surface roughness requirement (R_q)	$< 0.5 \text{ nm}$ (closure condition for Si, $\gamma = 100 \text{ mJ m}^{-2}$) [54]	$< 1 \text{ nm}$ (relaxed vs. direct bonding due to plasma-enhanced OH density) [55]	100 nm (polymer spin-coating planarises topography $> 90\%$ coverage) [56]
Bond energy / strength	$\gamma \approx 2200 \text{ mJ m}^{-2}$ at 1400 °C; $\sim 100 \text{ mJ m}^{-2}$ at room temperature [54]	$\gamma = 1.76 \text{ J m}^{-2}$ at 350 °C; $\gamma = 2.0\text{--}2.5 \text{ J m}^{-2}$ at room temperature with $\text{O}_2\text{+N}_2$ plasma [55]	$\sim 0.3\text{--}1.0 \text{ J m}^{-2}$ (die shear test; sufficient for substrate removal processing) [56]
Optical loss at interface at 1550 nm	$< 0.1 \text{ dB}$ (near-zero index contrast at Si/Si or InP/InP direct interface)	$< 0.1 \text{ dB}$ (oxide interlayer 10 nm)	$n_{\text{BCB}} \approx 1.535$ at 1550 nm; absorption negligible ($< 0.01 \text{ dB } \mu\text{m}^{-1}$) [56]
Thermal conductivity of bond layer	$\kappa_{\text{Si}} \approx 150 \text{ W m}^{-1} \text{ K}^{-1}$; direct contact, no interposing layer	$\kappa_{\text{oxide interlayer}} \approx 1.4 \text{ W m}^{-1} \text{ K}^{-1}$ (SiO_2 , 5–10 nm thick)	$\kappa_{\text{BCB}} \approx 0.29 \text{ W m}^{-1} \text{ K}^{-1}$ (significant thermal barrier for CW devices) [57]
Dielectric constant of bond layer	N/A (direct semiconductor contact)	$\epsilon_r \approx 3.9$ (native SiO_2 interlayer)	$\epsilon_r = 2.65$ at 1 GHz [57]
Void formation risk	Moderate; requires particle-free surface; voids $> 20 \text{ nm}$ unbridgeable [54]	Reduced vs. direct bonding; void-free yield 90–95 % at 350 °C [55]	Moderate; void-free bonding at 0.03, 0.6 N mm^{-2} pressure, 250 °C [58]
Primary application in III–V photonics	InP/InP or GaAs/Si homogeneous bonding; SOI wafer manufacture	InP/Si, GaAs/Si heterogeneous integration with CMOS compatibility	InP/InGaAsP on SOI; InGaAsP-OI (this work); AlGaAs-OI [56]

cured at $\sim 250^\circ\text{C}$ and offers the greatest tolerance to surface roughness and topography. BCB adhesive bonding is the method employed in this work owing to its low process temperature, excellent planarisation capability, optical transparency at 1550 nm, and chemical resistance to the HCl-based etchants used for InP substrate removal [56]. A detailed review of all three bonding techniques, their process parameters, bonding energies, and demonstrated III–V-on-insulator device results is presented in Chapter 2.

1.6 Applications of III–V Photonic Devices

III–V photonic devices have become fundamental components of modern optical technologies because they combine active optical functionality with strong electronic and nonlinear optical properties [38]. III–V semiconductors exhibit direct bandgap transitions that enable efficient light generation, amplification, and detection [7]. As a result, III–V materials such as InP [60], GaAs [23], AlGaAs [16], and InGaAsP [61] are widely used in photonic integrated circuits operating across visible, near-infrared, and telecommunications wavelength ranges.

One of the most important applications of III–V photonic devices is optical communication [23]. Semiconductor lasers fabricated from InP- and InGaAsP-based heterostructures are extensively used in fiber-optic communication systems operating near 1.3 and 1.55 μm . These wavelength ranges correspond to the low-loss transmission windows of silica optical fibers, enabling long-distance data transmission with minimal attenuation. III–V lasers are used in data centers, telecommunications networks, optical interconnects, and coherent communication systems. The direct bandgap nature of III–V semiconductors allows high optical gain and efficient electrically injected lasing, making them indispensable for integrated optical transmitters.

In addition to lasers, III–V materials are widely employed in semiconductor optical amplifiers (SOAs) [1]. These devices provide optical gain directly on-chip and are used for signal amplification, wavelength conversion, optical switching, and all-optical signal processing. SOAs are particularly attractive for integrated photonic circuits because they can amplify optical signals without requiring optical-to-electrical conversion [21]. Their compact size and compatibility with photonic integration make them important components in future high-capacity communication systems.

III–V photonic devices are also extensively used for optical modulation [1]. Electro-optic and electro-absorption modulators based on III–V quantum well structures can achieve high-speed modulation with large extinction ratios. In comparison to silicon modulators based on the free-carrier plasma effect, III–V modulators often exhibit stronger optical interaction and improved modulation efficiency. Electro-absorption modulators fabricated using

InGaAsP/InP quantum wells are especially important for high-speed telecommunications because they provide compact device footprints and low power consumption.

Photodetection represents another major application area for III–V semiconductors. InGaAs and InGaAsP photodetectors are widely used in optical receivers because of their high responsivity and sensitivity in the telecommunications wavelength range [23]. Avalanche photodiodes and high-speed photodetectors based on III–V materials are critical components in optical communication systems, coherent receivers, and sensing applications [5, 23]. The ability to monolithically integrate lasers, modulators, amplifiers, and photodetectors on a common III–V platform enables highly functional photonic integrated circuits.

Beyond conventional optical communication, III–V photonic devices have become increasingly important in nonlinear integrated photonics. Many III–V semiconductors exhibit strong second-order and third-order nonlinear optical coefficients, making them attractive for applications such as wavelength conversion, frequency comb generation, supercontinuum generation, optical parametric oscillation, and all-optical signal processing [62]. AlGaAs and InGaAsP waveguides, in particular, possess large Kerr nonlinearities and strong optical confinement, enabling highly efficient nonlinear interactions in compact integrated devices.

Four-wave mixing (FWM) is one of the most important nonlinear processes investigated in III–V waveguides [16]. In FWM, optical energy is transferred between interacting waves through the third-order nonlinear susceptibility of the material. This process enables wavelength conversion [14], signal processing [63], and parametric amplification [21]. Efficient FWM requires strong optical confinement, low propagation loss, and precise dispersion engineering [14]. High-index-contrast III–V-on-insulator platforms are especially attractive for this application because they provide reduced effective mode area and enhanced nonlinear interaction strength.

Second-harmonic generation (SHG) is another important nonlinear optical application of III–V semiconductors [64]. Unlike silicon, which lacks intrinsic second-order nonlinearity because of its centrosymmetric crystal structure, many III–V materials exhibit strong $\chi^{(2)}$ nonlinear response. This enables efficient frequency doubling and nonlinear frequency conversion processes. SHG has applications in optical signal processing, spectroscopy, quantum optics, and integrated frequency conversion systems.

III–V photonic devices also play a major role in microwave photonics and optical sensing [65, 23]. Integrated lasers, modulators, and photodetectors can be combined to generate, process, and detect microwave and millimeter-wave signals in the optical domain. These technologies are important for radar systems, wireless communication, and high-frequency signal processing [66]. In sensing applications, III–V photonic devices are used for biochemical sensing, environmental monitoring, gas detection, and LiDAR systems because of their

high optical sensitivity and broad wavelength coverage.

More recently, III–V photonic integrated circuits have attracted significant attention for quantum photonics and neuromorphic computing [62, 63]. Quantum light sources based on III–V quantum dots and nonlinear waveguides are being explored for integrated quantum communication and quantum information processing [67]. In addition, the ultrafast response and nonlinear properties of III–V materials make them promising candidates for photonic neural networks and optical computing architectures.

The development of III–V-on-insulator platforms further expands the range of applications by combining the active functionality of III–V semiconductors with the strong optical confinement of insulator-based waveguides [8]. These platforms enable compact nonlinear devices with enhanced light–matter interaction, reduced power consumption, and improved scalability. In particular, InGaAsP-on-insulator waveguides are highly promising for integrated nonlinear photonics because they combine telecommunication-band operation, strong Kerr nonlinearity, and compatibility with active photonic devices.

As integrated photonics continues to evolve, III–V materials are expected to remain essential for realizing multifunctional photonic integrated circuits that combine light generation, modulation, detection, amplification, and nonlinear optical processing on a single chip [64]. These capabilities motivate the investigation of InGaAsP-on-insulator platforms for nonlinear photonic applications presented in this thesis.

1.7 Thesis Outline

This thesis investigates the development of an InGaAsP-on-insulator (InGaAsP-OI) platform for nonlinear photonic applications, with emphasis on heterogeneous integration, fabrication challenges, and waveguide design for two complementary nonlinear optical processes. The thesis is organized into six chapters, as described below.

Chapter 1 introduces the fundamental concepts underpinning this work. It provides an overview of integrated photonics and the main material platforms, including silicon-on-insulator, silicon nitride, lithium niobate, and III–V compound semiconductors. Waveguide optics, nonlinear optical phenomena, including both second-order effects such as SHG and third-order effects such as FWM, and the fabrication technologies used in III–V photonic devices are introduced. A quantitative comparison of integrated photonic platforms is provided to motivate the development of InGaAsP-OI structures for nonlinear photonic applications.

Chapter 2 reviews III–V-on-insulator integrated photonic platforms, with emphasis on fabrication approaches and the state of the art. The chapter discusses general process flows for III–V-on-insulator integration, including direct wafer bonding, plasma-assisted bonding,

molecular bonding, and adhesive bonding using benzocyclobutene (BCB). It also reviews bonding challenges, substrate-removal methods, representative III–V-on-insulator device demonstrations reported in the literature, and the motivation for developing an InGaAsP-OI platform. Structural and surface characterization techniques (SEM, AFM, and EDX) are also discussed.

Chapter 3 presents the experimental fabrication work carried out in this thesis. It describes the process flow used to fabricate the InGaAsP-OI platform, including SiO₂ deposition, BCB coating, wafer bonding, and InP substrate removal. The chapter analyzes fabrication challenges including wet-etch-induced surface roughness, bonding defects, void formation, mechanical damage during substrate removal, and delamination at the BCB/SiO₂ interface, with particular attention to the chemical mechanism of AP3000 siloxane hydrolysis as the root cause of delamination. Mitigation strategies and process improvements are discussed.

Chapter 4 presents the design and numerical analysis of InGaAsP-OI waveguides for four-wave mixing (FWM) applications. The theory of degenerate FWM and parametric phase matching is introduced, followed by numerical simulation of waveguide geometry, effective mode area, and dispersion engineering using the finite-difference eigenmode (FDE) solver in Lumerical MODE. The dependence of group velocity dispersion and zero-dispersion wavelength on waveguide dimensions is investigated to optimize nonlinear interaction efficiency near telecommunications wavelengths. Fabrication tolerance analysis establishes the dimensional requirements for the lithography and bonding process. An optimized geometry ($w = 830$ nm, $h = 800$ nm) is identified, yielding a zero-dispersion wavelength of 1553 nm and a nonlinear coefficient of $\gamma \approx 36.9$ W⁻¹m⁻¹ for the TE₀₀ mode.

Chapter 5 presents the waveguide design for second-harmonic generation (SHG) in InGaAsP-OI waveguides, exploiting the non-centrosymmetric zinc-blende crystal structure of InGaAsP ($\bar{4}3m$ symmetry) which supports a large second-order nonlinear susceptibility ($d_{14} \approx 100$ – 200 pm/V). The chapter introduces the coupled wave equations governing SHG in a waveguide, derives expressions for conversion efficiency and modal phase-matching conditions, and identifies the phase-matched waveguide geometry through analytical effective index method simulations. A fundamental wavelength of 2.6 μ m is used, generating a second harmonic at 1.3 μ m—a wavelength pair lying within the transparency window of the InGaAsP composition used in this work. The TE₀₀ mode at the fundamental and the TM₀₁ mode at the second harmonic are identified as the optimal interacting pair, with phase matching achieved at a waveguide width of approximately 747 nm. Mode overlap integrals, effective mode areas, and SHG conversion efficiency are calculated, and fabrication tolerance requirements are established.

Chapter 6 summarizes the main contributions of this thesis and discusses future research directions for the continued development of InGaAsP-OI nonlinear photonic platforms, including improvements in fabrication reliability, the path toward realizing functional FWM and SHG devices, and advanced integrated photonic applications.

Chapter 2

III–V-on-Insulator Integrated Photonic Platforms: Fabrication Approaches and State of the Art

2.1 Introduction

This chapter provides an overview of the fabrication process for III–V-on-insulator integrated photonic platforms, the potential challenges associated with each fabrication step, and representative device outcomes demonstrated in existing studies.

III–V-on-insulator waveguide platforms exhibit superior integrated photonic device compactness, improved propagation losses, enhanced optical nonlinearity, and broader dispersion engineering capability compared to III–V heterostructures epitaxially grown on their native binary substrates [68, 15]. When a III–V semiconductor core is surrounded by a low-index oxide cladding, the large refractive index contrast, typically $\Delta n \approx 1.9$ for InGaAsP on SiO₂ enables sub-micron effective mode areas and tight bending radii that are not accessible on conventional InP or GaAs platforms. This confinement enhancement directly translates into larger nonlinear coefficients and greater flexibility to position the zero-dispersion wavelength (ZDW) through geometry alone.

The potential of this approach has been demonstrated convincingly in GaAs-on-insulator (GaAs-OI) and AlGaAs-on-insulator (AlGaAs-OI) platforms. Chiles *et al.* demonstrated second-harmonic generation (SHG) in GaAs-OI waveguides with a record single-pass efficiency of 40 W^{-1} [69], enabled by wafer-bonding-optimized low-loss waveguides fabricated on 76 mm wafers. Chang *et al.* demonstrated SHG normalised conversion efficiency of $200\% \text{ W}^{-1}\text{cm}^{-2}$ in AlGaAs-OI waveguides using modal phase matching [41]. Pu *et al.*

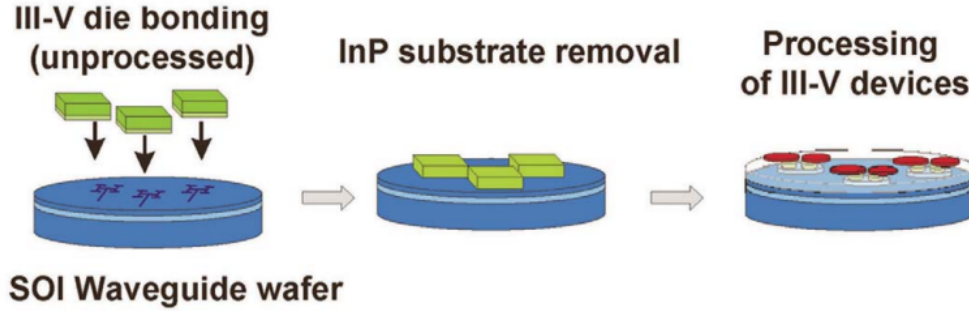


Figure 2.1: Schematic of the die-to-wafer bonding process for III–V-on-insulator integration, showing the three main steps: III–V die bonding onto an SOI carrier wafer, InP substrate removal, and lithographic processing of the III–V devices on the transferred epitaxial layer. Adapted from [7].

achieved ultra-efficient Kerr frequency comb generation in AlGaAs-OI microresonators with quality factors exceeding 10^6 [70], while the same platform has enabled ultra-broadband supercontinuum generation and photon-pair generation for quantum photonics [68]. These demonstrations establish III–V-OI bonded platforms as the leading approach for chip-scale nonlinear frequency conversion at telecommunications wavelengths.

The remainder of this chapter is organised as follows. Section 2.2 describes the general fabrication process flow for III–V-on-insulator platforms. Section 2.3 reviews the main bonding techniques and their associated challenges, supported by illustrative figures from the literature. Section 2.4 discusses approaches to binary substrate removal and their trade-offs. Section 2.5 presents representative successful III–V-OI device demonstrations. Section 2.6 provides the motivation and context for the specific InGaAsP-OI fabrication work reported in Chapter 3.

2.2 General Fabrication Process Flow for III–V-on-Insulator Platforms

The transfer of a III–V epitaxial layer from its native binary substrate onto an insulating SiO_2/Si carrier follows a common three-stage sequence regardless of the specific bonding technique employed.

Stage 1: Epitaxial growth. The III–V device layer (e.g. AlGaAs, GaAs, or InGaAsP) is grown by molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD) on a lattice-matched binary substrate (GaAs or InP). A sacrificial etch-stop layer

is typically included between the substrate and the device layer to provide high selectivity during substrate removal. Precise control of layer thickness, composition, and interface quality at this stage is critical, because the final waveguide geometry, and therefore its dispersion and nonlinear performance—is set during growth [34, 71].

Stage 2: Wafer bonding. The III–V wafer is bonded face-down onto a SiO_2/Si carrier wafer. Depending on the technique, an intermediate bonding layer (BCB, SiO_2 , or none) is used to join the surfaces. Bonding is performed under controlled temperature, pressure, and atmosphere. The choice of bonding method has a direct impact on surface quality requirements, thermal budget, and susceptibility to interfacial defects, as discussed in Section 2.2.1.

Stage 3: Binary substrate removal. The original binary substrate (InP or GaAs) is removed by a combination of mechanical lapping and selective wet or dry etching, exposing the III–V device layer on the insulating platform. This step is typically the most mechanically and chemically demanding in the process flow, and its outcome is the primary determinant of the bonded-layer surface quality available for subsequent waveguide lithography.

Figure 2.1 illustrates the overall die-to-wafer bonding sequence, showing III–V die placement onto the SOI carrier, InP substrate removal, and the final lithographically processed III–V device layer. The specific implementation of each stage, and in particular the choice of bonding technique and substrate removal chemistry, determines the final platform quality and yield. Several bonding approaches have been developed for III–V heterogeneous integration, each with distinct advantages, limitations, and sensitivity to surface quality. This section reviews the three most widely used methods in the context of III–V-OI photonic platforms: direct wafer bonding, plasma-assisted and molecular bonding, and adhesive bonding using benzocyclobutene (BCB). A comparative summary is provided in Table 2.2.

2.2.1 Direct Wafer Bonding

Direct wafer bonding is one of the earliest techniques used for heterogeneous integration of III–V semiconductors [72, 73]. In this approach, two ultra-clean and atomically smooth surfaces are brought into direct contact under controlled temperature and pressure, allowing intermolecular van der Waals interactions to initiate bonding, followed by stronger covalent bond formation during thermal annealing. A schematic of the process is shown in Figure 2.2.

Direct bonding provides excellent thermal conductivity and strong mechanical stability because no intermediate bonding layer is introduced between the wafers, making it attractive for high-power photonic devices. However, the method requires extremely low surface roughness (typically below 0.5 nm RMS), as well as strict control of particles, contamination, and surface planarity. Even small surface defects can lead to void formation and bonding

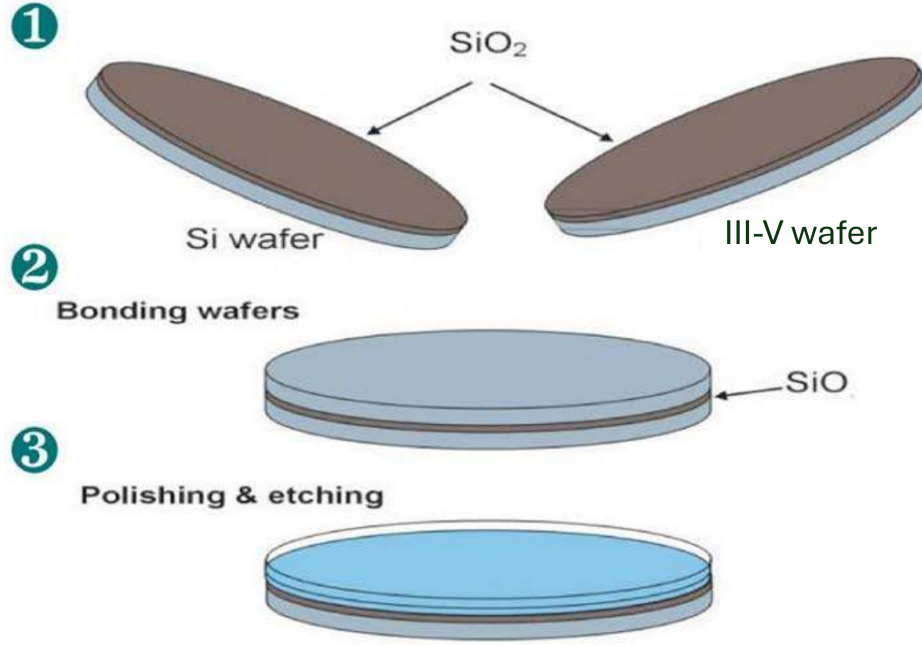


Figure 2.2: Schematic illustration of the direct wafer bonding process for III–V-on-insulator integration [74].

failure [75, 76]. For III–V-on-insulator platforms based on InGaAsP, achieving such ideal surfaces after wet etching and dielectric deposition steps is often difficult in a laboratory setting, limiting the practical applicability of direct bonding at small scale.

An additional challenge specific to III–V/Si heterogeneous systems is the large thermal expansion coefficient mismatch: for example, InP ($\alpha \approx 4.6 \times 10^{-6} \text{ K}^{-1}$) bonded to silicon ($\alpha \approx 2.6 \times 10^{-6} \text{ K}^{-1}$) generates significant interfacial shear stress during the high-temperature annealing required to strengthen the bond [77]. This can initiate crack formation and reduce bonding reliability, particularly for large-area wafers. Although wafer bonding enables the integration of heterogeneous material platforms with high optical performance, the process is highly sensitive to surface contamination, roughness, and trapped particles. Imperfections introduced during bonding can lead to localized voids, delamination, and mechanical non-uniformities, which negatively affect device reliability and optical performance. Figure 2.3 illustrates typical bonding defects caused by particle contamination during wafer bonding.

2.2.2 Plasma-Assisted and Molecular Bonding

To relax the strict surface requirements of direct bonding, plasma-assisted bonding techniques have been introduced [79, 80]. In this method, oxygen or nitrogen plasma treatment

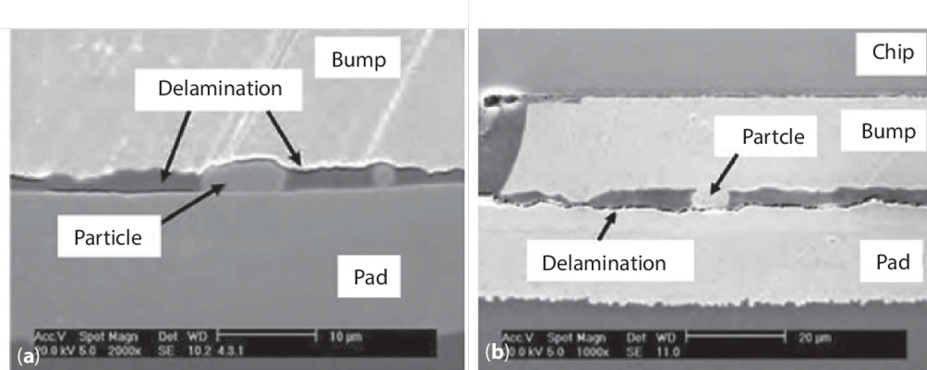


Figure 2.3: Cross-sectional SEM images showing typical wafer bonding defects caused by particle contamination. Trapped particles between the bonding interfaces can generate localized bumps and delamination regions, leading to poor bonding quality and reduced device reliability. Adapted from [78].

is used to activate wafer surfaces before bonding. Plasma activation increases surface energy and improves hydrophilicity, thereby enhancing interfacial bonding strength even when surfaces are not perfectly ideal. Molecular bonding follows a similar principle and often involves hydroxyl-terminated oxide surfaces that form strong Si–O–Si bonds during annealing. The mechanism and process flow are illustrated schematically in Figure 2.4.

Plasma-assisted bonding is widely used in silicon photonics and III–V integration platforms because of its improved bonding strength and reduced sensitivity to minor surface imperfections. The technique has been demonstrated for InP-to-Si integration at temperatures below 300 °C, enabling the transfer of InP-based active devices onto silicon photonic circuits [80, 7].

Despite these advantages, plasma-assisted bonding still requires careful optimization of surface preparation and plasma conditions. Excessive plasma exposure may introduce surface damage and interface defects that degrade optical performance. Furthermore, thermal expansion mismatch between III–V materials and silicon substrates can generate significant interfacial stress during post-bonding annealing, which may lead to crack formation and reduced long-term reliability [82]. For InGaAsP bonded to silicon, the lattice and thermal mismatch challenges that apply to direct bonding are not fully eliminated and must be managed through controlled temperature ramping and appropriate bonding geometry.

2.2.3 Adhesive Wafer Bonding Using BCB

Among the available bonding methods, adhesive bonding using benzocyclobutene (BCB) has become one of the most widely adopted techniques for III–V-on-insulator fabrication [75,

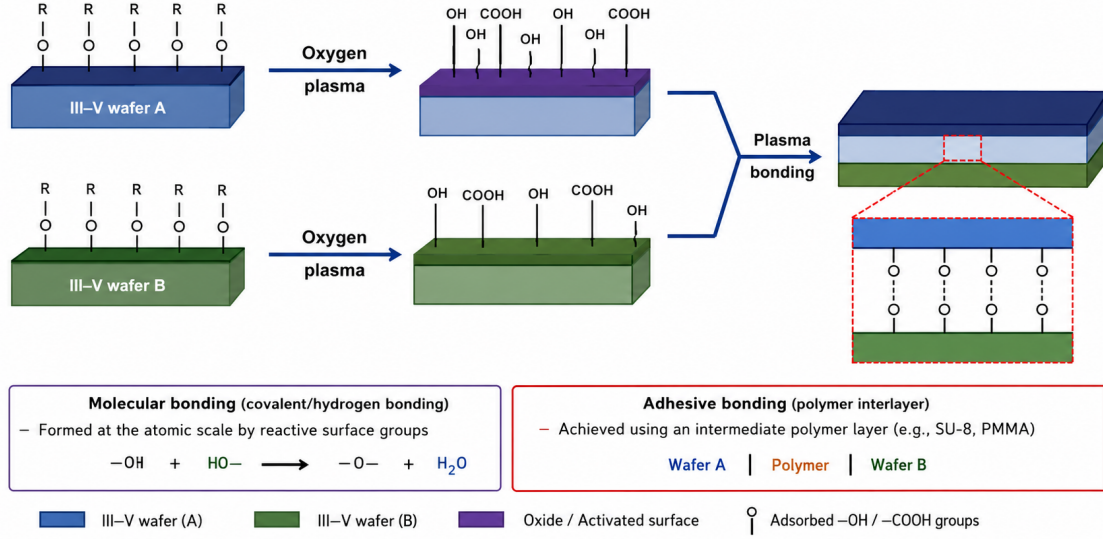


Figure 2.4: Schematic illustration of plasma-assisted and molecular bonding [81].

83, 76]. BCB is a thermosetting polymer commonly used in microelectronics and MEMS packaging because of its favorable optical, electrical, and mechanical properties.

BCB exhibits a low dielectric constant of approximately 2.65, low optical loss at telecommunications wavelengths, excellent planarization capability, and curing temperatures typically between 180 °C and 300 °C [78]. Unlike direct bonding, BCB does not require atomically smooth surfaces: the polymer layer can accommodate surface roughness and compensate for small topographical variations, significantly improving fabrication tolerance. This makes BCB particularly attractive for integrating III–V layers onto SiO_2/Si substrates after the roughness increase inevitably introduced by wet etching and dielectric deposition. A schematic of the adhesive bonding process is shown in Figure 2.5.

A typical BCB bonding process involves surface cleaning and dehydration baking, application of an adhesion promoter (typically AP3000), spin-coating of diluted BCB, partial curing to stabilise the polymer flow, wafer alignment, bonding under vacuum with applied force, and final thermal curing. The BCB layer thickness must be carefully controlled because it directly influences both optical confinement and mechanical reliability: a thinner layer improves optical mode confinement and reduces the risk of mode leakage into the silicon substrate, while a thicker layer provides better mechanical compliance and reduces stress concentration at the interface.

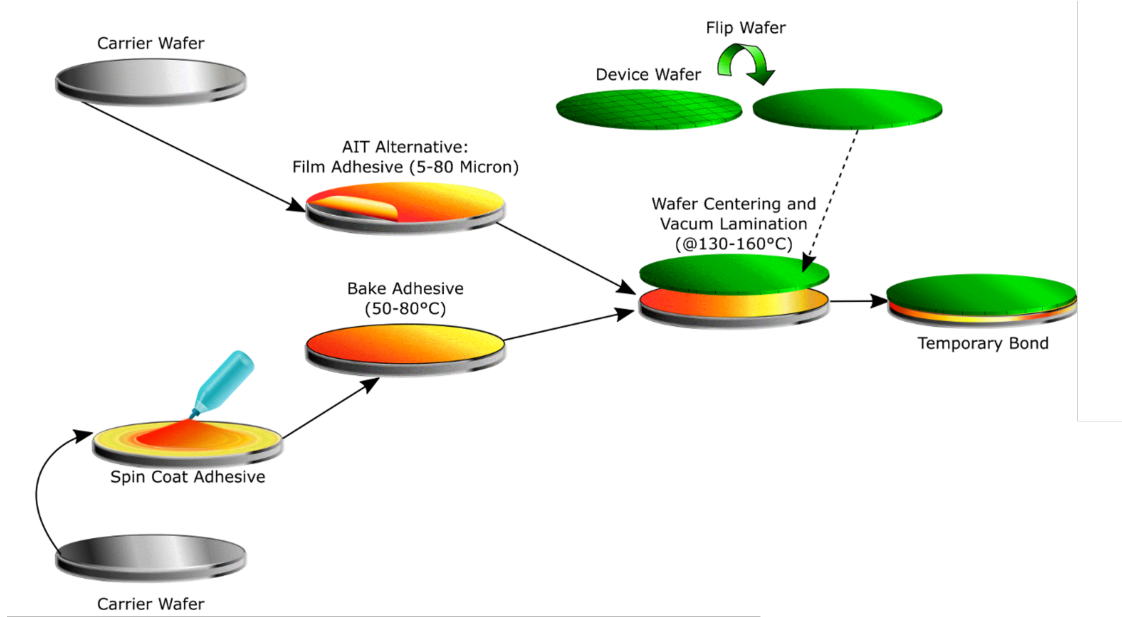


Figure 2.5: Schematic illustration of adhesive wafer bonding [84].

2.2.4 Bonding Challenges Reported in Literature

Despite the advantages of BCB bonding, several reliability challenges are commonly reported in the literature for III–V-on-insulator fabrication [78, 35]. The major challenges and their corresponding mitigation strategies are summarized in Table 2.1.

Interfacial delamination is the most frequently reported failure mode for BCB-bonded III–V-OI platforms. Although BCB itself is chemically resistant to common etchants such as HCl and H_2SO_4 , the adhesion promoter layer used to strengthen the BCB/ SiO_2 interface is significantly more sensitive to prolonged acid exposure. AP3000 relies on siloxane (Si-O-Si) bond chemistry, and these bonds hydrolyse under sustained contact with HCl or H_2SO_4 solutions, weakening adhesion and promoting interfacial separation [86, 87]. Importantly, delamination typically becomes visible only during substrate removal or extended wet processing, rather than during bonding itself, making it difficult to anticipate from early-stage inspection alone.

Mechanical stress arising from thermal expansion mismatch between InP ($\alpha \approx 4.6 \times 10^{-6} \text{ K}^{-1}$), BCB ($\alpha \approx 42 \times 10^{-6} \text{ K}^{-1}$), SiO_2 ($\alpha \approx 0.55 \times 10^{-6} \text{ K}^{-1}$), and Si ($\alpha \approx 2.6 \times 10^{-6} \text{ K}^{-1}$) generates significant shear stress during curing and cooling cycles [88]. These stresses can initiate crack formation, particularly at pre-existing surface defects or lapping-induced microstructural damage.

Void formation during bonding is primarily associated with non-uniform pressure distribution, trapped air at the bonding interface, and incomplete BCB flow during curing. Voids create local stress concentration points that can develop into delamination during subsequent

Table 2.1: Major fabrication challenges encountered in BCB-bonded III–V-on-insulator platforms and corresponding mitigation strategies reported in the literature [85, 35].

Challenge	Primary cause	Mitigation strategy
Surface roughness increase	Aggressive wet etching of InP capping layer	Optimised etch chemistry; ICP smoothing step
Delamination at BCB/SiO ₂ interface	Acid attack on AP3000 adhesion promoter	Plasma activation of oxide; acid-resistant silane promoters
Void formation during bonding	Non-uniform pressure; trapped air; incomplete cure	Controlled bonding force; slow temperature ramp; vacuum environment
Over-thinning of active layer	Prolonged wet chemical etching	Real-time thickness monitoring; hybrid lapping + ICP removal
Optical mode leakage	Excessively thick BCB bonding layer	Minimise BCB thickness through dilution; post-cure thinning
Mechanical cracking during lapping	Excessive lapping pressure or coarse slurry	Fine slurry and low-pressure lapping; force feedback control

processing. Vacuum bonding and slow temperature ramp protocols substantially reduce void formation by allowing the BCB to flow uniformly before crosslinking is complete [78].

Several studies have shown that bonding reliability can be improved through a combination of plasma activation of the SiO₂ surface prior to adhesion promoter deposition, careful optimization of partial curing temperature and duration, and controlled reduction of wet chemical exposure time during substrate removal [35]. These strategies are directly relevant to the InGaAsP-OI fabrication work reported in Chapter 3.

Table 2.2: Comparison of bonding techniques for III–V-on-insulator photonic integration. Surface roughness tolerance values are approximate and depend on bonding area and force applied [89, 20].

Method	Roughness tolerance	Cure temperature	Interlayer	Key limitation
Direct bonding	< 0.5 nm RMS	> 600 °C	None	Strict surface flatness
Plasma-assisted	< 1 nm RMS	200–400 °C	None	Thermal stress at III–V/Si
BCB adhesive	< 5 nm RMS	180–300 °C	BCB polymer	Acid-induced delamination

2.3 Binary Substrate Removal: Methods and Trade-offs

Following successful bonding, the original binary substrate must be removed to expose the III–V device layer. This step is typically the most mechanically and chemically demanding in the entire process flow. Table 2.3 summarizes the most commonly used substrate removal methods for InP- and GaAs-based III–V-OI platforms, together with their key advantages and limitations.

Table 2.3: Comparison of substrate removal methods for III–V-on-insulator platforms. Selectivity values are approximate and depend on composition, temperature, and etchant concentration [85, 23, 35, 47].

Method	Target substrate	Advantages	Limitations
Wet etching (HCl: 1:3)	InP	High selectivity over InGaAsP; simple setup	Acid penetration at interface; roughness increase; limited precision
Wet etching (citric acid/)	GaAs	Selectivity up to 500× over AlGaAs [17]	Slow etch rate; composition-sensitive selectivity
Mechanical lapping	InP or GaAs	Removes bulk material quickly; reduces wet etch time	Risk of microcracks; requires precise force control
ICP dry etching (Cl ₂ /Ar)	InP or GaAs	Anisotropic etching; limited chemical exposure to interface	Plasma damage; requires optimisation of RF power and gas ratio
Hybrid (lapping + wet + ICP)	InP or GaAs	Best balance of speed, selectivity, and interface protection	Process complexity; requires multiple fabrication tools

Wet chemical etching is the most widely used approach because of its simplicity and high selectivity. For InP substrates, HCl: (1:3) provides etch rates on the order of 1 $\mu\text{m}/\text{min}$ with excellent selectivity over InGaAsP, stopping cleanly at an InGaAsP or InGaAs etch-stop layer. For GaAs substrates, citric acid/ mixtures are commonly used, offering selectivity of up to 500× over AlGaAs etch-stop layers [23]. The principal disadvantages of wet etching are the risk of acid penetration into the bonding interface during extended processing, increasing surface roughness, and limited precision in the final layer thickness.

Mechanical lapping is typically combined with wet etching: the substrate is first lapped to within approximately 50 μm of the device layer to reduce wet etching time, and then the

remaining substrate is removed chemically. This hybrid approach reduces acid contact time at the bonding interface, but introduces the risk of lapping-induced microcracks if the applied pressure and slurry selection are not controlled carefully. Continuous thickness monitoring throughout the lapping process is essential to avoid over-thinning.

Inductively coupled plasma (ICP) etching using Cl_2/Ar or $\text{Cl}_2/\text{CH}_4/\text{H}_2$ gas mixtures offers superior etch-rate control and reduced chemical exposure compared to wet etching. ICP processes can selectively remove InP with good precision, limiting the duration of aggressive chemical contact with the bonding interface. The main trade-offs are plasma-induced surface damage under aggressive conditions and the need for careful RF power and gas chemistry optimization [47].

In practice, a **hybrid approach** which consists of mechanical lapping followed by brief selective wet etching, and finally an ICP finishing step, providing the best balance of speed, selectivity, and interface protection. The total acid contact time is minimized while the precision of the final layer thickness is maintained through the dry etch step. This hybrid strategy is recommended for InGaAsP-OI fabrication and forms the basis of the process improvements proposed in Chapter 3.

2.4 Representative III–V-on-Insulator Device Demonstrations

The bonding and substrate removal approaches described above have enabled a range of high-performance III–V-OI devices. Table 2.4 summarises selected representative demonstrations from the literature to contextualise the state of the art and motivate the specific platform developed in this thesis.

GaAs-OI nonlinear waveguides. Chiles *et al.* [91] demonstrated SHG in GaAs-OI strip waveguides fabricated via direct wafer bonding of MBE-grown GaAs onto SiO_2/Si . A record single-pass conversion efficiency of 40 W^{-1} was achieved at a pump wavelength near $2.0 \mu\text{m}$ by optimising propagation losses to below 1 dB/cm through careful control of the bonding interface and etching conditions.

AlGaAs-OI nonlinear waveguides and microresonators. Chang *et al.* [41] achieved an SHG normalised conversion efficiency of $200\% \text{ W}^{-1}\text{cm}^{-2}$ in AlGaAs-OI waveguides using modal phase matching, exploiting the large $\chi^{(2)}$ of AlGaAs in the zinc-blende crystal class. Pu *et al.* [70] demonstrated ultra-high- Q microresonators with quality factors exceeding 10^6 and efficient Kerr frequency comb generation at milliwatt pump thresholds on the same platform. Mobini *et al.* [90] further extended the AlGaAs-OI demonstration to ultra-broadband

Table 2.4: Representative III–V-on-insulator device demonstrations from the literature. Conversion efficiency values are normalised unless stated otherwise. N/A = not reported in the cited work.

Platform	Device type	Bonding method	Key result	Reference
GaAs-OI	SHG waveguide	Direct bonding	$\eta = 40 \text{ W}^{-1}$ (single-pass)	Chiles <i>et al.</i> [69]
AlGaAs-OI	SHG waveguide	BCB adhesive	$\eta = 200\% \text{ W}^{-1}\text{cm}^{-2}$	Chang <i>et al.</i> [41]
AlGaAs-OI	Microresonator (Kerr comb)	BCB adhesive	$Q > 10^6$; comb generation at mW threshold	Pu <i>et al.</i> [70]
AlGaAs-OI	Supercontinuum waveguide	BCB adhesive	Octave-spanning supercontinuum at 50 mW pump power	Mobini <i>et al.</i> [90]
InGaAsP/InP	Passive waveguide (FWM)	N/A (native substrate)	$\gamma \approx 36 \text{ W}^{-1}\text{m}^{-1}$ at 1550 nm	Mobini <i>et al.</i> [18]

supercontinuum generation, all-optical wavelength conversion, and photon-pair generation for quantum photonic applications, confirming the versatility of BCB-bonded III–V-OI platforms across a range of nonlinear optical processes.

InGaAsP-OI ring resonators. Studies have recently analyzed $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ -on-insulator ring resonators for frequency comb generation at 1550 nm. Free-carrier absorption was identified as the primary intracavity loss mechanism, and a p–n junction reverse bias was proposed as a mitigation strategy [92]. These results confirm InGaAsP-OI as a viable platform for nonlinear photonic integration at telecommunications wavelengths, and highlight fabrication reliability as the principal remaining barrier to device-grade performance.

InGaAsP passive waveguides on native substrate. Mobini *et al.* [18] characterised C-band nonlinear optical interactions in InGaAsP/InP waveguides on the native InP substrate, reporting a nonlinear coefficient $\gamma \approx 36 \text{ W}^{-1}\text{m}^{-1}$ and measuring the TPA coefficient $\beta_{\text{TPA}} \approx 19 \text{ cm/GW}$ at 1550 nm. These material parameter measurements provide the quantitative foundation for the waveguide design work presented in Chapter 4 of this thesis, and motivate the transfer of this material onto a high-index-contrast insulator platform to further reduce the effective mode area and enhance the nonlinear interaction strength.

2.5 Motivation for InGaAsP-OI Development

The demonstrations reviewed in Section 2.4 establish that the III–V-OI platform concept is mature for GaAs and AlGaAs, but the realization of InGaAsP-on-insulator via BCB adhesive

bonding remains at an early stage. Interfacial reliability during substrate removal and consistent bonding yield are the principal open challenges. Nevertheless, InGaAsP is particularly attractive for nonlinear photonics at telecommunications wavelengths because its bandgap can be engineered by tuning the quaternary alloy composition, providing a direct route to reducing two-photon absorption while preserving a large Kerr nonlinearity, which represents an advantage not available in AlGaAs-OI at 1550 nm, where the bandgap of the commonly used $\text{Al}_{0.18}\text{Ga}_{0.82}\text{As}$ composition places the half-bandgap energy very close to the photon energy [15]. Furthermore, the direct bandgap of InGaAsP enables monolithic integration of on-chip pump lasers and semiconductor optical amplifiers alongside the passive nonlinear waveguides, a capability that distinguishes InGaAsP-OI from both silicon-on-insulator and silicon nitride platforms.

The work presented in Chapter 3 of this thesis addresses these fabrication challenges directly. It reports the development and characterization of an InGaAsP-OI platform fabricated using BCB adhesive bonding, documents the fabrication challenges encountered, identifies the root cause of the delamination failures observed in cross-sectional SEM imaging, and proposes a revised process strategy for future fabrication iterations.

2.6 Conclusions

This chapter reviewed the fabrication process flow for III–V-on-insulator photonic platforms, with particular emphasis on the bonding techniques and substrate removal strategies applicable to InGaAsP-on-insulator integration. Three bonding approaches were discussed: direct wafer bonding (stringent surface requirements, excellent thermal conductivity), plasma-assisted and molecular bonding (improved tolerance, residual thermal stress), and BCB adhesive bonding (the most practical for laboratory-scale III–V-OI fabrication due to its low processing temperature and tolerance to surface roughness). Binary substrate removal methods were compared, with the hybrid lapping-plus-ICP approach identified as the most favorable balance of speed, selectivity, and interface protection.

Representative device demonstrations in GaAs-OI, AlGaAs-OI, and InGaAsP-OI platforms were presented, establishing the technological state of the art and confirming that the primary remaining challenge for InGaAsP-OI is bonding reliability during substrate removal. The material parameters for $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ reported in the literature were identified as the quantitative foundation for the nonlinear waveguide designs presented in Chapter 4. These observations directly motivate the fabrication process development and failure analysis reported in the following chapter.

Chapter 3

Fabrication of the InGaAsP-on-Insulator Platform: Process Development, Challenges, and Mitigation

3.1 Introduction

The work reported in this chapter constitutes the original experimental contribution of this thesis to the fabrication of the InGaAsP-on-insulator material platform. The objective was to develop a reliable process for transferring $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ epitaxial layers from their native InP substrate onto SiO_2/Si carrier wafers using benzocyclobutene (BCB) adhesive bonding, as a first step toward realizing the nonlinear photonic device designed in Chapter 4.

BCB was selected as the bonding medium because of its demonstrated compatibility with III–V-OI fabrication (Chapter 2), its low processing temperature, and its tolerance to the surface roughness introduced during InP capping layer removal. The target outcome was a bonded InGaAsP/ SiO_2 /BCB/Si stack with sufficient structural integrity to survive InP substrate removal and subsequent waveguide lithography.

This chapter reports the specific process flow used (Section 3.2), the bonding results and challenges encountered (Section 3.3), the wet etching recipe development and its limitations (Section 3.4, and proposed improvements for future fabrication iterations (Section 3.5).

3.2 Experimental Process Flow

The fabrication process developed in this work consists of five steps, illustrated schematically in Figure 3.1:

1. **InP capping layer removal.** The available epitaxial wafer contained a 300 nm InP capping layer above the 800 nm InGaAsP active layer. This cap had been included for a previous project and was therefore not required for the present InGaAsP-on-insulator waveguide structure. Because using available wafers avoided the high cost and long lead time associated with custom epitaxial growth, the cap layer was removed prior to bonding. The InP cap was selectively wet etched using an $\text{HCl}:\text{H}_3\text{PO}_4$ (1:3) solution for approximately 18 s in order to expose the underlying InGaAsP surface. The InP capping layer was not part of the intended final InGaAsP-on-insulator waveguide structure. It was present because the epitaxial wafers used in this work had originally been grown for a different project that required an InP cap layer. Since epitaxial growth of custom III–V wafers is expensive and time-consuming, this work relied on wafers already available within the research group rather than ordering a new epitaxial structure. As a result, the 300 nm InP capping layer had to be removed prior to SiO_2 deposition and BCB bonding in order to expose the InGaAsP surface required for the transferred InGaAsP-on-insulator platform.
2. **SiO_2 deposition.** A 320 nm SiO_2 layer is deposited on the InGaAsP surface by PECVD; a 2 μm SiO_2 layer is deposited on the Si carrier wafer. Both layers serve as the optical undercladding in the final waveguide structure.
3. **BCB coating and partial curing.** AP3000 adhesion promoter is applied to both wafers, followed by spin-coating of BCB (diluted 1:8 in T-1100 mesitylene) at 5000 rpm. A partial cure at 150°C for 2 hours under $\text{O}_2 < 100$ ppm is performed to stabilise the polymer before bonding.
4. **Wafer bonding.** The wafer pair is bonded in a vacuum bonder under 200–500 N force, ramping from 180°C to a final curing temperature of 280°C for 2 hours.
5. **InP substrate removal.** The InP substrate is first thinned by mechanical lapping, then removed by selective wet etching in $\text{HCl}:\text{H}_3\text{PO}_4$.

The material stack prior to bonding consists of: 300 nm InP cap / 800 nm InGaAsP / 370 μm InP substrate (III–V side) bonded to 2 μm SiO_2 / Si carrier (carrier side), with the BCB layer between the two SiO_2 surfaces.

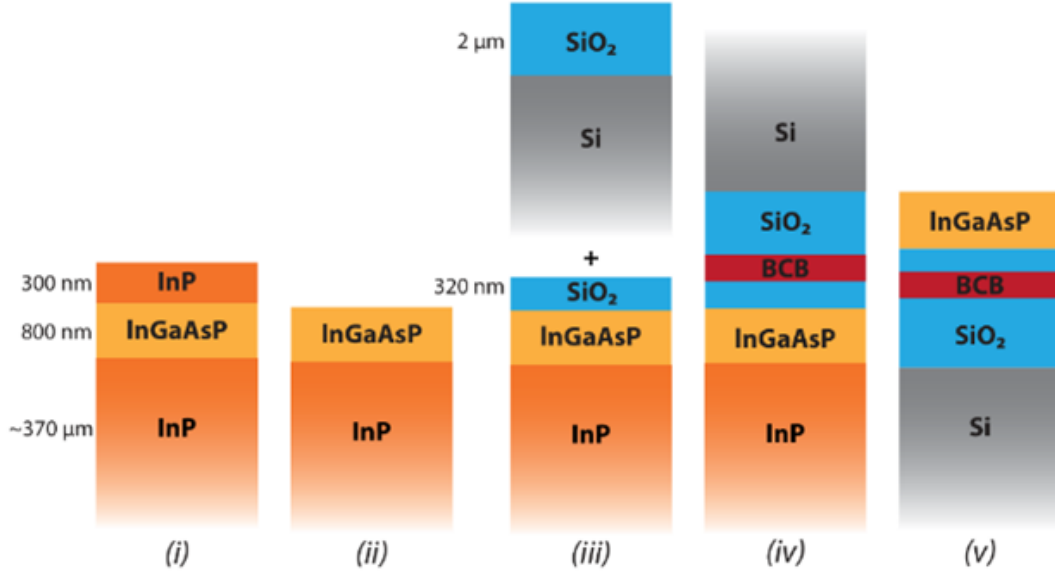


Figure 3.1: Schematic of the InGaAsP-OI based waveguides fabrication process: i) InP/InGaAsP stack, ii) InP capping layer removal, iii) SiO₂ deposition and BCB coating on stack and carrier wafer, iv) Wafer bonding and v) Etching of InP substrate.

3.3 Bonding Process: Results, Challenges, and Recipe Optimization

This section documents the bonding outcomes observed experimentally, the failure modes encountered, and the process adjustments implemented in response. Scanning electron microscopy (SEM), atomic force microscopy (AFM), and energy-dispersive X-ray spectroscopy (EDX) characterization results are presented as the primary evidence used to identify the root causes of bonding failure and to motivate the process improvements discussed in Section 3.3.

Although benzocyclobutene (BCB) adhesive bonding provides a practical and widely adopted approach for III-V-on-insulator integration, several fabrication challenges significantly affected bonding reliability and the final device quality in this work. The most critical issues observed were: (i) surface roughness introduced during the InP capping layer etch; (ii) non-uniform bonding interfaces; (iii) mechanical damage during substrate removal; and (iv) interfacial delamination. These problems are strongly interconnected, as defects originating from earlier fabrication steps propagate and become amplified during the bonding and substrate removal processes.

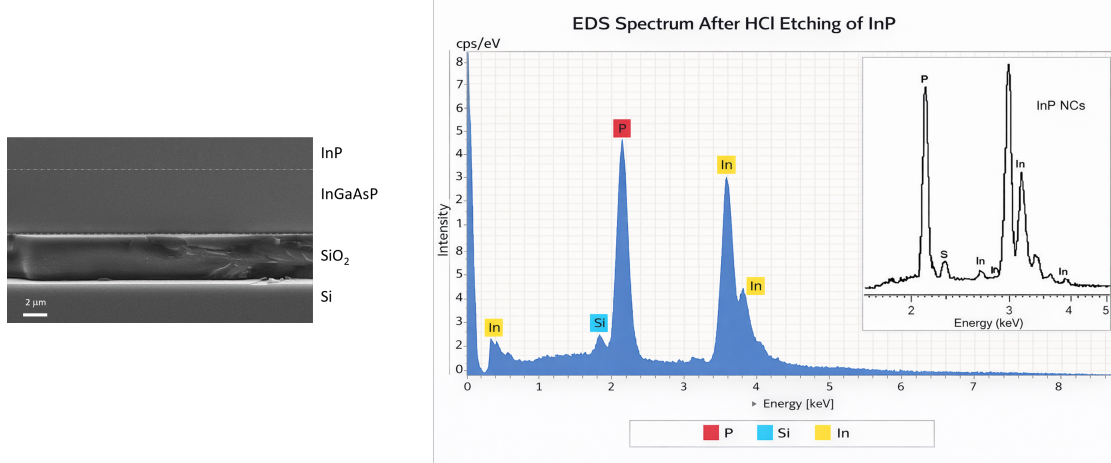


Figure 3.2: (Left) SEM image of the bonded InGaAsP/SiO₂/BCB/Si sample after wafer bonding, showing successful heterogeneous integration of the III-V stack onto the silicon carrier substrate. (Right) Energy-dispersive X-ray spectroscopy (EDX) analysis of the bonded structure after HCl etching, confirming the elemental composition of the sample and verifying the presence of key constituent elements such as indium (In), phosphorus (P), and silicon (Si).

3.3.1 Surface Roughness After Wet Etching

One of the earliest and most significant challenges appears during the removal of the InP capping layer using wet chemical etching. Although HCl:H₃PO₄ provides good selectivity for InP over InGaAsP, aggressive etching conditions and prolonged exposure can significantly increase surface roughness.

Experimental observations show that the RMS roughness increases from approximately 0.707 nm before etching to 1.751 nm after etching. Figure 3.3 presents the SEM and AFM analysis of the InGaAsP stack after removal of the InP capping layer using HCl:H₃PO₄ wet etching. In particular, Fig. 3.3 (a) shows the surface morphology after etching, where an increase in roughness can be observed after the chemical removal of the InP cap layer. This roughness increase is critical because it directly reduces the effective bonding contact area between the InGaAsP layer and the SiO₂/BCB interface, leading to localized stress concentration points that can initiate crack formation and interfacial delamination during wafer bonding and substrate removal. After etching, the surface becomes rough due to the non-uniform chemical reaction between the acid solution and the InP layer. Fig. 3.3(a) shows the etched surface morphology, where localized defects and increased surface irregularities can be observed. This increase in roughness is important because it reduces the effective bonding contact area and creates localized stress concentration points, which increase the probability of crack initiation and interfacial delamination during wafer bonding and sub-

strate removal. The increase is caused by non-uniform chemical reactions, local variations in etchant concentration, and the formation of micro-defects during acid exposure. Higher roughness reduces the effective contact area between the bonded layers and creates localized stress concentration points.

These rough regions become preferred locations for crack initiation during wafer bonding and substrate removal. In addition, rough surfaces increase optical scattering losses and reduce waveguide performance in the final device. For high-quality bonding, maintaining surface roughness below approximately 1 nm RMS is highly desirable.

To mitigate this issue, precise control of etching time and acid concentration is required. Replacing prolonged wet etching with optimized dry etching techniques such as inductively coupled plasma (ICP) etching can further improve surface quality and reduce interface degradation.

InGaAsP-specific etching challenges relative to AlGaAs-based platforms. During the doctoral examination, Prof. de Lafontaine raised the question of what fabrication challenges are specific to InGaAsP, and how they differ from those encountered in the more mature AlGaAs-on-insulator (AlGaAs-OI) platform. Several factors compound the surface roughness problem and make BCB bonding of InGaAsP inherently more challenging than that of AlGaAs.

First, InP substrate removal requires HCl:H₃PO₄ chemistry, which is significantly more aggressive toward polymer bonding interfaces than the citric acid/H₂O₂ mixtures used for GaAs substrate removal from AlGaAs-OI platforms. Citric acid/H₂O₂ provides excellent selectivity (up to 500× over AlGaAs etch-stop layers [17]) at a lower acid activity, reducing the rate of AP3000 siloxane hydrolysis at the bonding interface. In contrast, HCl is a strong acid that hydrolyses Si–O–Si bonds rapidly even at room temperature [93]. This intrinsic difference in etch chemistry means that InGaAsP-OI fabrication carries a fundamentally higher delamination risk during substrate removal than AlGaAs-OI under otherwise equivalent process conditions.

Second, the InP capping layer commonly present on as-grown InGaAsP wafers—as in this work, where a 300 nm InP cap had to be removed prior to bonding, introduces an additional wet etch step not required in GaAs-based platforms. This extra HCl:H₃PO₄ exposure occurs on the InGaAsP surface before SiO₂ deposition and BCB coating, increasing the cumulative roughness from 0.71 nm to 1.75 nm RMS. Furthermore, HCl may not be perfectly inert to InGaAsP at the termination of the InP etch. Although the selectivity of HCl for InP over InGaAsP is high, it is not infinite: local compositional fluctuations in the quaternary alloy In_{0.86}Ga_{0.14}As_{0.3}P_{0.7} can yield slightly non-uniform etch termination,

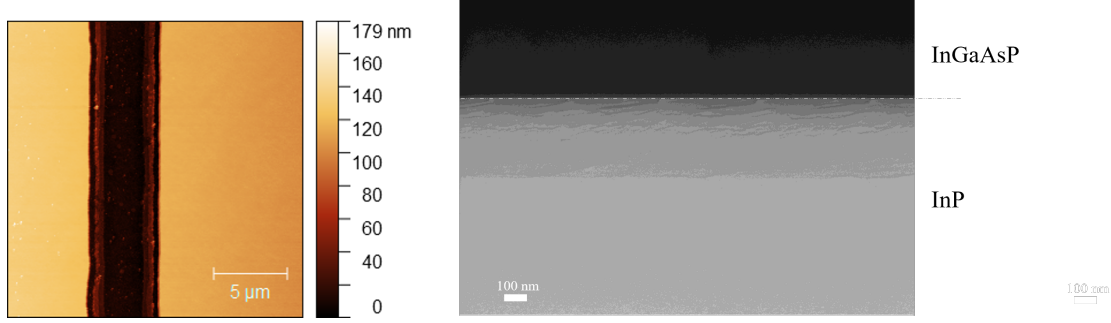


Figure 3.3: SEM and AFM images of the stack after InP capping layer etching with HCl and H_3PO_4

leaving pits or roughened patches on the InGaAsP surface that act as nucleation sites for subsequent delamination [44].

Third, the quaternary alloy composition of InGaAsP makes its etch behaviour more sensitive to composition inhomogeneity introduced during MOCVD growth than binary or ternary III–V materials. Variations in alloy composition across the wafer translate directly into spatial variation in etch rate and surface energy, producing less predictable surface morphology after wet etching than AlGaAs or InP surfaces under equivalent conditions [17].

These InGaAsP-specific challenges, including the aggressive substrate etch chemistry, multi-step acid exposure history, and quaternary composition sensitivity, explain why achieving a defect-free, delamination-resistant BCB/SiO₂ interface is more difficult in InGaAsP-OI than in AlGaAs-OI, and motivate the process improvements proposed in Section 6.

3.3.2 Influence of BCB Thickness On Optical Performance

The thickness of the BCB bonding layer influences both the mechanical stability and the optical performance of III–V-on-insulator waveguides, though through different physical mechanisms. Variations in BCB thickness affect the separation between the InGaAsP guiding layer and the underlying substrate, which can influence bonding reliability during fabrication and subsequent processing, as discussed below.

It is worth clarifying the role of BCB thickness in optical confinement specifically, since this is not, by itself, the dominant factor. Vertical confinement of the guided mode is governed primarily by the refractive index contrast at the InGaAsP/BCB interface, rather than by the distance between the InGaAsP core and the silicon substrate. Because the refractive index of cured BCB ($n_{\text{BCB}} \approx 1.54$) is substantially lower than that of the InGaAsP core ($n_{\text{core}} = 3.35$), a strong index contrast and therefore strong vertical confinement. This is established as soon as the BCB layer is present beneath the core. The evanescent tail

of the guided mode decays exponentially into the BCB layer and is effectively attenuated within tens of nanometres of the core/BCB boundary. Consequently, once the BCB layer thickness exceeds this decay length, additional BCB thickness does not meaningfully alter the confinement of the mode, since the mode never reaches the lower portion of the layer in either case. BCB layer thickness is therefore not, on its own, the parameter that determines optical confinement in this waveguide stack; rather, confinement is set by the presence and index of the BCB layer at the immediate core boundary.

This does not mean BCB thickness is optically irrelevant in practice. Non-uniformity in BCB thickness across the wafer, rather than its nominal value, is the more direct concern: local thickness variation can introduce non-uniform effective cladding conditions along the waveguide length, contributing to coupling inefficiency, additional scattering, and modal mismatch when interfacing III–V waveguides with passive silicon photonic components in heterogeneous integration platforms [62]. Maintaining uniform BCB thickness during spin-coating and bonding is therefore important for consistent device performance, even though the nominal thickness itself has limited direct influence on confinement.

From a mechanical perspective, BCB thickness plays a more direct and better-established role. Excessively thin BCB layers may compromise adhesion strength and increase the risk of interfacial failure during thermal cycling, curing, and substrate removal. Thin bonding layers are less capable of accommodating surface non-uniformities and thermal stress, which can promote delamination at the bonding interface, as discussed further in Section following section. Conversely, thicker BCB layers provide better mechanical compliance and help reduce stress concentration, improving bonding reliability. The selection of BCB thickness in practice therefore involves a trade-off that is primarily mechanical—between adhesion robustness and the planarization/uniformity requirements of the process—rather than an optical trade-off in confinement.

Previous studies have shown that both BCB thickness and the degree of partial curing prior to bonding strongly influence bonding uniformity and mechanical reliability, as illustrated in Fig. 3.4 [94]. Thinner BCB layers exhibit increased sensitivity to bonding non-uniformity and interfacial stress, while the degree of BCB cross-linking prior to bonding affects the polymer flow behaviour and thermal stability during curing [94, 20]. These factors directly influence void formation, bonding quality, and long-term structural stability.

In this work, the BCB layer thickness was controlled through dilution of the polymer (1:8 in T-1100 mesitylene) and spin coating at 5000 rpm, resulting in an estimated bonding layer thickness on the order of a few hundred nanometers. This thickness was selected as a compromise between optical confinement and mechanical bonding reliability. Although thinner BCB layers are generally desirable for improved nonlinear optical confinement, ex-

cessively thin bonding layers were found to increase susceptibility to interfacial defects and delamination during substrate removal and wet etching. The selected process therefore prioritized sufficient mechanical stability while maintaining acceptable optical confinement for the intended InGaAsP-on-insulator waveguide platform.

Therefore, the optimization of BCB thickness requires a careful balance between optical performance and mechanical stability. While thinner BCB layers are generally preferred for enhanced confinement and nonlinear efficiency, sufficient thickness must be maintained to ensure robust adhesion and long-term structural reliability.

Optical Properties of BCB as a Function of Cure Degree

An important material property of the BCB bonding layer not previously accounted for in the waveguide simulations is its refractive index. Unlike a fixed dielectric constant, the refractive index of benzocyclobutene (DVS-BCB, Cyclotene 3022 series) is not a fixed quantity: it depends on the degree of crosslinking achieved during thermal curing and on the curing method employed. Understanding this dependence is important. It is crucial to investigate the conditions under which $n_{\text{BCB}} = 1.54$ was obtained, and whether it could change with curing time and spinning conditions.

DVS-BCB cures through a thermally activated cycloaddition mechanism. During heating, the cyclobutene rings of the DVS-BCB monomer open to form highly reactive *o*-xylylene di-radicals, which then undergo [4+2] Diels–Alder cycloaddition with neighbouring vinyl groups, forming a densely crosslinked aromatic network [95]. As crosslink density increases with temperature and duration, the free volume of the polymer network decreases and its electronic polarizability falls, causing the refractive index to decrease. This explains the apparently counterintuitive result that more fully cured BCB has a *lower* refractive index than partially cured BCB.

For the non-photosensitive Cyclotene 3022 formulation used in this work, optical characterization studies report a refractive index of $n_{\text{BCB}} \approx 1.54\text{--}1.56$ at 1553 nm for fully cured films (250 °C, 1 h, N₂ atmosphere), measured by prism coupling (Metricon) and confirmed by FTIR spectroscopy [96]. This value is substantially higher than the SiO₂ lower cladding index ($n_{\text{SiO}_2} = 1.444$ at 1550 nm), which served as the implicit BCB index in the original simulations.

The dependence on curing method is significant. Yahya et al. showed that oven curing of BCB 4024-40 films produces a refractive index change of approximately 1.49 % across the cure cycle (final values $n = 1.545\text{--}1.568$), while hotplate curing under comparable peak temperatures yields only a 0.1 % change owing to incomplete crosslinking (final $n \approx 1.570$) [97]. The higher index of hotplate-cured BCB reflects residual monomer and partial crosslinks that

retain higher polarizability. Separately, Foothill Instruments report that the index difference between a soft cure (partial crosslinking) and a hard cure (near-complete crosslinking) can be as large as 2 % ($\Delta n \approx 0.03$ at telecom wavelengths) [96].

The degree of cure in the BCB layer at each stage of the bonding process is a critical process parameter. Infrared spectroscopic ellipsometry (IRSE) studies in the context of 3D-interconnect technology have confirmed that a partial cure step analogous to the 150 °C soft-bake used in this work yields approximately 50–60 % crosslink conversion, while post-bonding curing at 250–280 °C drives the BCB to near-complete conversion, as confirmed by the transformation of the BCB cyclobutene stretching absorption into the fully aromatic tetrahydronaphthalene (THN) peak in the FTIR spectrum [98]. The pre-cure step is essential for bonding quality: the degree of polymerization must not exceed approximately 50 % before bonding is attempted, because an over-cured layer loses its ability to flow under compression and cannot achieve intimate contact with the opposing surface [99].

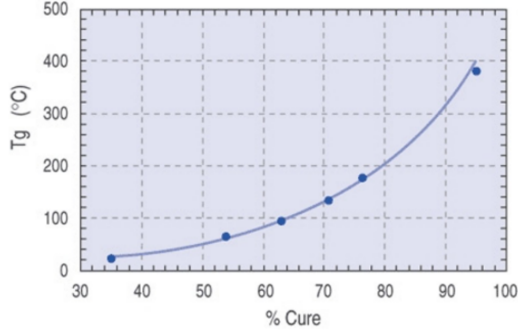
The bonding chemistry of AP3000 adhesion promoter is also relevant here. AP3000 is vinyltriacetoxysilane [$\text{CH}_2=\text{CH}-\text{Si}(\text{OCOCH}_3)_3$], which hydrolyses in the presence of ambient moisture to form silanol groups (Si–OH). These condense with Si–OH groups on the SiO_2 surface to form strong siloxane bridges (Si–O–Si) that anchor BCB to the oxide [95]. The vinyl group of the hydrolysed AP3000 then participates in Diels–Alder cycloaddition with the *o*-xylylene intermediates generated from DVS-BCB during thermal curing, chemically locking the polymer network to the interface [95]. The interfacial siloxane bonds formed by AP3000 are the same bond type as those attacked by HCl during substrate removal, which is the root cause of the delamination described previously.

For the process used in this work, partial cure at 150 °C for 2 h followed by final cure at 280 °C under vacuum in the wafer bonder, the BCB bonding layer is expected to approach near-complete cure post-bonding, placing n_{BCB} in the range 1.54–1.55 at 1550 nm. Ellipsometry, ideally infrared spectroscopic ellipsometry (IRSE), performed on a BCB film prepared under the same process conditions would provide a direct, experimentally confirmed value and is recommended as a process characterization step for future fabrication iterations.

3.3.3 Wafer Bonding Defects and Void Formation

Wafer bonding introduces additional challenges related to interface uniformity and defect formation[78]. Non-uniform pressure distribution, trapped air, incomplete BCB curing, and poor surface preparation can all lead to void formation and localized bonding failure.

Voids inside the bonding interface are particularly problematic because they create weak points that may later develop into delamination during substrate removal or wet chemical



BCB thickness	BCB cross-linking prior to bonding	BCB thickness non-uniformity after bonding
2.6 μm	35 %	~ 10 % of nominal BCB thickness
2.6 μm	43 %	~ 0.40 % of nominal BCB thickness
0.6 μm	35 %	~ 15 % of nominal BCB thickness
0.6 μm	43 %	~ 0.42 % of nominal BCB thickness

Figure 3.4: (Left) Dependence of the glass transition temperature (T_g) of BCB on the degree of cure prior to bonding. Increasing cross-linking results in higher T_g , which influences polymer flow behaviour, bonding uniformity, and thermal stability during wafer bonding. Adapted from the literature. (Right) Influence of BCB thickness and pre-bonding cross-linking percentage on post-bonding BCB thickness non-uniformity. Thinner BCB layers exhibit increased sensitivity to non-uniformity and bonding defects, highlighting the trade-off between optical confinement and mechanical reliability in III–V-on-insulator wafer bonding processes. Adapted from [94].

processing. Thermal expansion mismatch between InP, InGaAsP, BCB, SiO₂, and silicon further increases the mechanical stress around these defects during heating and cooling cycles.

Careful control of bonding parameters is therefore essential. Partial curing before bonding helps preserve polymer flow and improve interface uniformity, while slow temperature ramping reduces thermal stress accumulation. Vacuum bonding conditions minimize trapped air and improve large-area interface quality.

Uniform application of bonding pressure and proper surface cleaning prior to bonding are also critical for reducing void formation and ensuring reproducible fabrication results.

3.3.4 Mechanical Damage During Substrate Removal

The removal of the thick InP substrate is one of the most delicate steps in the entire fabrication process. Mechanical lapping is necessary to reduce substrate thickness before final wet etching, but excessive pressure or poor abrasive control can introduce microcracks, surface damage, and local stress concentrations.

These defects may propagate into the active InGaAsP layer or along the bonding interface, significantly increasing the risk of delamination. In addition, over-thinning during lapping can compromise structural integrity and make the bonded stack more vulnerable to fracture during handling.

The final wet etching step used to remove the remaining InP also introduces risk. Prolonged HCl exposure allows acid penetration into interfacial micro-defects and weakens the

adhesion promoter layer, accelerating crack propagation along the BCB/SiO₂ interface.

To reduce these risks, fine abrasive slurry, low applied pressure, continuous thickness monitoring, and controlled lapping speed should be used. Combining mechanical thinning with shorter and more selective wet etching steps improves both process safety and final interface quality.

3.3.5 Delamination Mechanisms at the BCB/SiO₂ Interface

Delamination remains the most critical reliability challenge in BCB-bonded InGaAsP-on-insulator structures. Although BCB itself is chemically stable and generally resistant to common acids such as HCl and H₃PO₄, the weakest region is often not the polymer itself, but rather the adhesion-promoted BCB/SiO₂ interface. The commonly used adhesion promoter AP3000 relies on siloxane (Si–O–Si) bonding chemistry to improve polymer adhesion to oxide surfaces. These bonds are significantly more sensitive to prolonged acid exposure than the BCB polymer itself.

During substrate removal and wet chemical etching, acid can penetrate through interfacial defects or micro-imperfections, degrade the adhesion promoter, and initiate interfacial separation. Delamination is therefore often observed after successful bonding rather than during the bonding step itself, becoming visible only during substrate removal or extended wet processing.

Mechanical factors further contribute to delamination. Thermal expansion mismatch between the III–V semiconductor layers, the BCB polymer, and the silicon substrate generates interfacial shear stress during curing, heating, and cooling cycles. These stresses can initiate crack formation, particularly at weak bonding interfaces. In addition, mechanical lapping during substrate thinning may introduce localized stress and microcracks, which can propagate rapidly along the weakest interface, typically the BCB/SiO₂ region.

Surface roughness also plays an important role in bonding reliability. Figure 3.5 shows the SEM image and corresponding EDX elemental analysis of the etched InGaAsP surface after substrate removal. The SEM image reveals the post-etching surface morphology and highlights localized features that may contribute to interfacial defects during bonding. Small bright spots observed on the surface may correspond to residual particles, localized roughness, or minor etching non-uniformities, which can later act as initiation points for crack propagation and delamination. The EDX analysis confirms the dominant presence of indium (In) and phosphorus (P), verifying successful exposure of the InGaAsP layer after substrate removal, while minor oxygen content is attributed to surface oxidation. This analysis supports the importance of maintaining surface quality during etching to preserve bonding

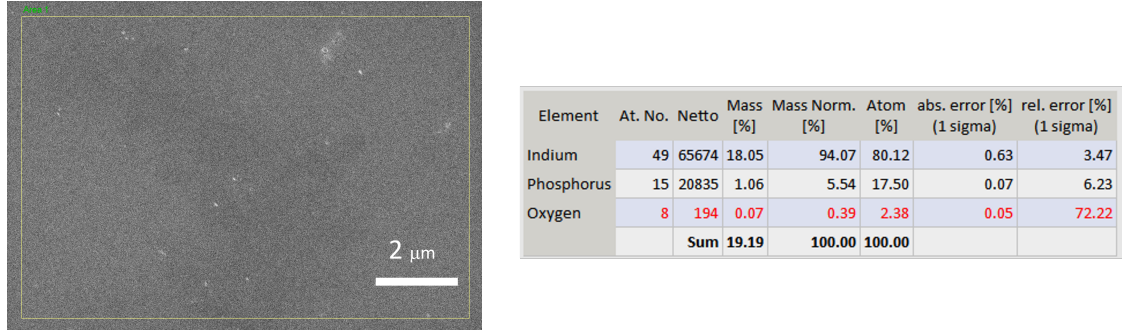


Figure 3.5: Scanning electron microscopy (SEM) image and corresponding energy-dispersive X-ray spectroscopy (EDX) elemental analysis of the etched InGaAsP surface after substrate removal. The SEM image shows the surface morphology and localized features that may contribute to interfacial defects during bonding. The relatively uniform surface indicates acceptable etching quality, while small bright spots may correspond to residual particles or localized roughness. The EDX results confirm the dominant presence of indium (In) and phosphorus (P), with minor oxygen content attributed to surface oxidation. This analysis verifies the material composition and provides insight into the chemical effects of the etching process.

reliability. Aggressive wet etching and mechanical processing can increase surface roughness, reducing the effective contact area between bonded layers. As roughness increases, localized stress concentrations develop more easily, facilitating crack initiation and propagation along the interface.

Improving interface chemistry is therefore one of the most important directions for process optimization. Alternative silane adhesion promoters, plasma activation of oxide surfaces, controlled thermal ramping, reduced acid exposure time, and careful management of surface roughness can significantly improve long-term bonding stability and reduce the risk of interfacial delamination. Thermal expansion mismatch further contributes to delamination by generating shear stress during heating and cooling cycles. Once microcracks form, crack propagation occurs rapidly along the weakest interface, typically the BCB/SiO₂ region.

This explains why delamination is frequently observed after successful bonding rather than during the bonding step itself. The problem often becomes visible only during substrate removal or extended wet chemical processing.

Improving interface chemistry is therefore one of the most important directions for process improvement. Alternative silane promoters, plasma activation of oxide surfaces, and reduced acid exposure time can significantly improve long-term bonding stability.

Delamination during cleaving and polishing. The interfacial delamination observed in the cross-sectional SEM images may not in all cases have been initiated during HCl/H₃PO₄

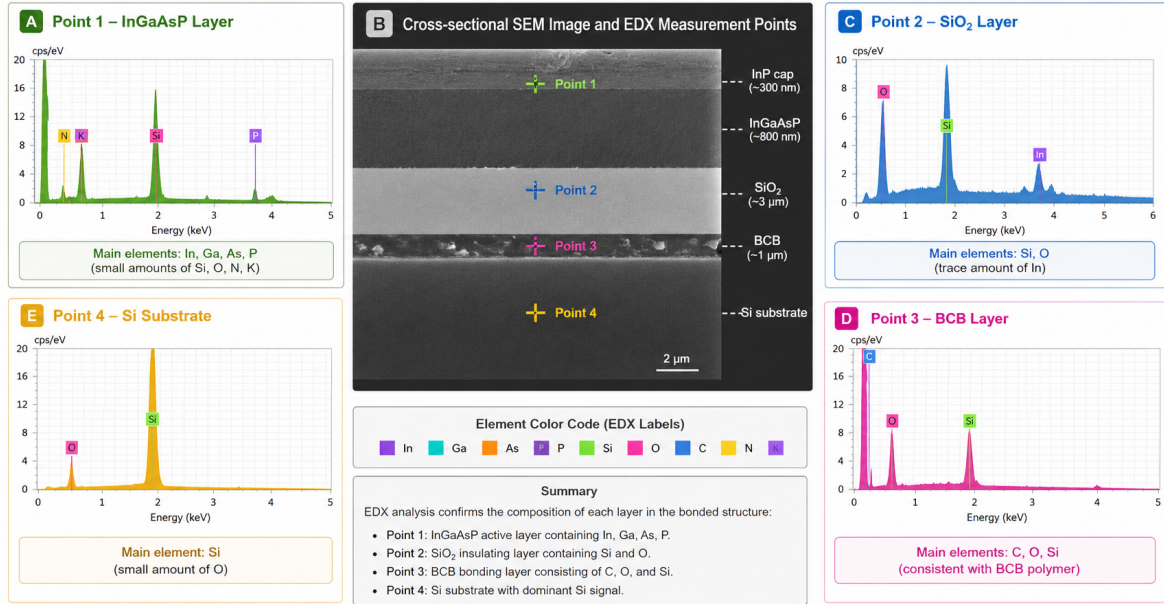


Figure 3.6: Multi-point cross-sectional scanning electron microscopy (SEM) image and corresponding energy-dispersive X-ray spectroscopy (EDX) analysis of the bonded InGaAsP-on-insulator structure. The central SEM image shows the full bonded stack, including the InP cap layer, InGaAsP active layer, SiO₂ insulating layer, BCB bonding layer, and silicon substrate, with EDX measurement points identified across each region. Point 1 corresponds to the InGaAsP layer and confirms the presence of indium (In), gallium (Ga), arsenic (As), and phosphorus (P). Point 2 corresponds to the SiO₂ layer and shows dominant silicon (Si) and oxygen (O) peaks. Point 3 represents the BCB bonding interface, where carbon (C), oxygen (O), and silicon (Si) signals are observed, confirming the polymer bonding layer. Point 4 corresponds to the silicon substrate and shows a strong silicon signal. The analysis confirms successful layer transfer, verifies the material composition of each region, and demonstrates the structural integrity of the bonded III–V-on-insulator platform.

wet etching. Accumulated stress in the BCB layer may instead trigger or amplify delamination during sample preparation by diamond-scribe cleaving or mechanical polishing. Conventional cleaving propagates a crack front along the $\{110\}$ crystallographic plane of InP under a mechanical impulse load. In the presence of residual thermal shear stress at the BCB/SiO₂ interface, arising from the large thermal expansion coefficient mismatch between InP ($\alpha \approx 4.6 \times 10^{-6} \text{ K}^{-1}$), BCB ($\alpha \approx 42 \times 10^{-6} \text{ K}^{-1}$), SiO₂ ($\alpha \approx 0.55 \times 10^{-6} \text{ K}^{-1}$), and Si ($\alpha \approx 2.6 \times 10^{-6} \text{ K}^{-1}$), the mechanical impulse of cleaving can initiate or extend pre-existing delamination nuclei along the polymer/oxide interface.

Focused ion beam (FIB) milling eliminates this mechanical impulse entirely. FIB removes material by physical sputtering rather than crack propagation and produces facets with sub-100 nm roughness in III–V semiconductor structures without introducing mechanical stress [52]. Adopting FIB for waveguide facet preparation in future InGaAsP-OI samples would therefore serve two purposes: it removes a potential artefact source from the cross-sectional SEM analysis of the bonding interface, and it provides higher-quality end-fire coupling facets for optical characterisation. The absence of mechanical contact during FIB milling is particularly important for bonded structures, where the interface is the weakest mechanical link.

Effect of the etchant on the SiO₂ layer. Prof. Kim also raised the question of whether HCl/H₃PO₄ attacks not only AP3000 but also the SiO₂ undercladding layer itself. Under standard process conditions, thermally grown SiO₂ is resistant to dilute HCl: the etch rate in HCl is negligible compared to its rate in HF. However, the SiO₂ layers in this work were deposited by plasma-enhanced chemical vapour deposition (PECVD), which produces an amorphous, slightly porous film with higher defect density than thermal oxide. Concentrated or hot phosphoric acid can attack PECVD SiO₂ through these micropores even at moderate temperatures, and prolonged HCl:H₃PO₄ exposure at room temperature may introduce slow oxide dissolution along grain boundaries and defect clusters in the PECVD film. This would progressively weaken the SiO₂/BCB interface even in the absence of bulk oxide removal. Determining the relative contributions of AP3000 siloxane hydrolysis and PECVD SiO₂ surface attack requires a controlled experiment in which AP3000 is omitted and the BCB/SiO₂ interface is exposed to the etchant for varying durations, with bonding strength assessed by four-point bending after each exposure. This experiment is recommended for future process development.

3.4 Wet Etching Recipe Development and Challenges

The InP substrate removal step was the critical point at which most bonding failures occurred in this work. This section documents the etching recipe used, the problems observed, and their diagnosis. Wet etching was initially selected because of its simplicity and the high selectivity of $\text{HCl}:\text{H}_3\text{PO}_4$ for InP over InGaAsP, with etch rates on the order of approximately $1\text{ }\mu\text{m}/\text{min}$ depending on processing conditions [85]. The InP substrate removal process proceeded in two stages: mechanical lapping to reduce substrate thickness, carried out by our postdoc at the University of Waterloo, followed by selective wet etching to clear the remaining InP. While the bonded structure initially exhibited good mechanical integrity, prolonged exposure to $\text{HCl}/\text{H}_3\text{PO}_4$ during substrate removal resulted in significant interfacial degradation and partial delamination, as shown in the cross-sectional SEM images of Figure 3.6. The bonded stack consists of the transferred InGaAsP layer supported by a SiO_2/BCB bonding interface on a silicon carrier substrate. While the bonded structure initially exhibited good mechanical integrity, prolonged exposure to hydrochloric acid (HCl) and phosphoric acid (H_3PO_4) during substrate removal resulted in significant interfacial degradation and partial delamination of the bonded layers.

The InP substrate removal process was performed using $\text{HCl}:\text{H}_3\text{PO}_4$ solutions with high selectivity for InP over InGaAsP. Wet etching was initially selected because of its simplicity and relatively high selectivity. However, extended exposure to the acidic solution was found to progressively weaken the bonding interface and introduce structural instability within the bonded stack.

Although benzocyclobutene (BCB) itself is generally chemically stable and relatively resistant to acidic environments, the bonding reliability strongly depends on the adhesion promoter layer used between BCB and the SiO_2 surface. In this work, AP3000 adhesion promoter was applied prior to BCB spin coating in order to improve interfacial adhesion and promote uniform bonding between the oxide surface and the polymer layer. Adhesion promoters are particularly important in BCB bonding because untreated oxide surfaces often exhibit insufficient chemical affinity with the polymer, which can lead to poor bonding strength, void formation, or delamination during thermal processing.

AP3000 promotes adhesion primarily through siloxane ($\text{Si}-\text{O}-\text{Si}$) bonding interactions at the oxide interface. However, these siloxane-related interfacial bonds are significantly more sensitive to prolonged acid exposure than the bulk BCB polymer itself. During extended $\text{HCl}/\text{H}_3\text{PO}_4$ etching, acid penetration through micro-defects, interfacial voids, or mechanically damaged regions can gradually degrade the adhesion-promoting layer. This weakens the BCB/ SiO_2 interface and increases susceptibility to crack propagation and delamination.

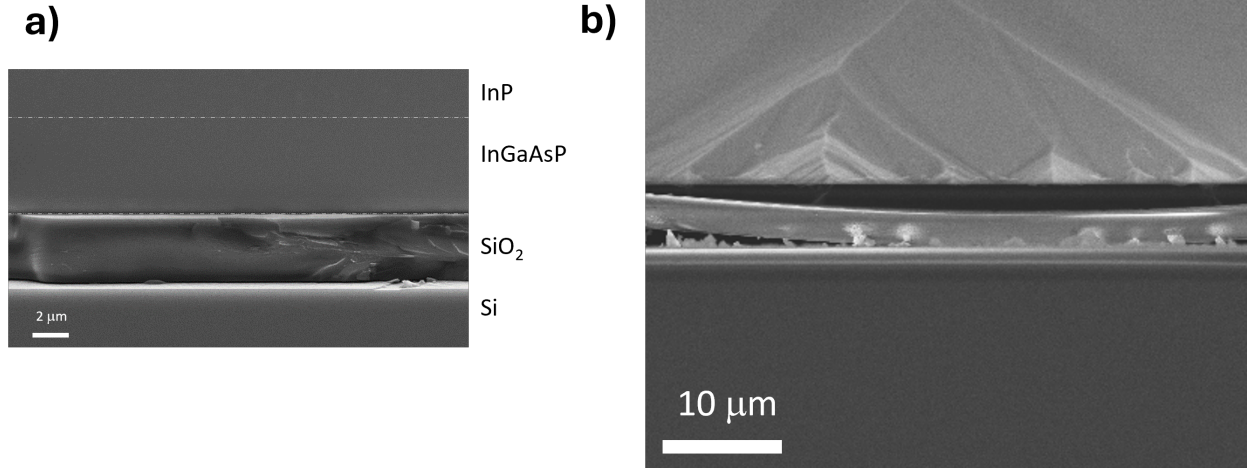


Figure 3.7: Cross-sectional SEM images of the bonded InGaAsP-on-insulator structure before and after prolonged wet chemical etching of the InP substrate. The images illustrate the degradation of the bonded interface and the onset of interfacial delamination following extended exposure to $\text{HCl}/\text{H}_3\text{PO}_4$ etching solutions. Prolonged acid exposure weakens the BCB/ SiO_2 bonding interface, leading to structural instability and separation of the bonded layers.

In addition, mechanical lapping performed prior to wet etching may introduce localized stress concentrations, micro-cracks, and surface defects that further facilitate acid infiltration into the bonding interface. The combined effects of prolonged chemical exposure, interfacial degradation, and mechanical stress contribute to progressive separation of the bonded layers, as observed in Figure 3.7. The SEM images suggest that over-etching and excessive substrate thinning can significantly compromise the structural integrity of the InGaAsP-on-insulator platform.

These observations highlight the importance of carefully controlling wet etching duration, surface preparation, and bonding conditions in III–V-on-insulator fabrication processes. They also demonstrate that interfacial reliability is governed not only by the intrinsic stability of BCB, but also by the long-term chemical stability of the adhesion-promoting interface under aggressive wet chemical processing conditions.

3.4.1 Strategies for Mitigating Delamination

To address the delamination challenges, several mitigation strategies have been proposed in the literature and were further discussed during the doctoral examination. The following strategies are organised in order of expected impact on bonding reliability.

Plasma activation of the SiO₂ surface prior to AP3000 application. O₂ or N₂ plasma treatment of the SiO₂ surface immediately before AP3000 deposition increases the density of silanol (Si–OH) groups available for condensation with the AP3000 vinyltriace-toxysilane, thereby increasing the initial siloxane bond density at the BCB/oxide inter-face [95]. A higher siloxane bond density raises the critical fracture energy required to initiate delamination and slows the rate of acid-induced hydrolysis by increasing the mean path length between accessible Si–O–Si bonds. Dow Chemical’s own processing guidelines recommend O₂ plasma activation as a standard step when the SiO₂ surface has been exposed to ambient air for more than a few hours after deposition [96]. This step was not included in the process and represents the highest-priority single-step improvement.

Reduction of HCl exposure time via hybrid substrate removal. Replacing extended wet etching with a sequence of mechanical lapping (to $\sim 50\ \mu\text{m}$), brief selective wet etching (to $\sim 5\ \mu\text{m}$), and ICP-RIE finishing (Cl₂/Ar) eliminates the bulk of the acid exposure while maintaining etch selectivity. Keyvaninia et al. demonstrated that ultra-thin BCB bonding layers ($< 60\ \text{nm}$) survive InP substrate removal in HCl without delamination when the acid exposure time is kept below 10 min through pre-thinning by mechanical lapping [100]. Although the thicker BCB layers used in the present work require longer exposure, the hybrid approach substantially reduces the acid contact time compared to full wet etching of a $\sim 370\ \mu\text{m}$ InP substrate.

Alternative acid-resistant adhesion promoters. The siloxane-based chemistry of AP3000 is intrinsically susceptible to hydrolysis in acidic environments because Si–O–Si bonds are thermodynamically unstable in the presence of water at low pH [93]. An alternative strategy is to use silane coupling agents with alkyl or fluoroalkyl spacer groups that provide hydropho-bic protection of the Si–O–Si bond, reducing the rate of hydrolytic attack. Organotitanate and organozirconate adhesion promoters have been reported to offer higher hydrolytic sta-bility than silane-based systems in comparable applications, though their compatibility with BCB curing conditions and photonic device processing requires validation before adoption in InGaAsP-OI fabrication.

Mechanical testing as a process gate before substrate removal. As recommended by Prof. Kim, introducing systematic mechanical characterisation of bonded substrates be-fore committing to the destructive substrate removal step would add a quantitative quality gate to the process. Four-point bending (4PB) tests measure the interfacial fracture energy (in J m^{-2}) by propagating a controlled crack along the bonded interface under a well-defined

bending moment, and have been proposed as a standardised method for assessing die-to-wafer and wafer-to-wafer bond quality [101, 102]. A minimum fracture energy threshold of approximately $1\text{--}2\text{ J m}^{-2}$, typical for adhesively bonded III–V/Si interfaces, could be established as a pass/fail criterion before InP substrate removal, reducing yield loss from delamination during processing. Nanoindentation on the bonded cross-section provides complementary local information on interface adhesion and has been recently applied to BCB/Cu hybrid bonding structures [102].

BCB planarisation and its effect on the bonding interface. One aspect of the BCB layer that works in favour of bonding reliability is its planarising behaviour: spin-coated BCB flows to fill surface topography before crosslinking is complete, accommodating surface roughness up to approximately 5 nm RMS without compromising adhesion [100]. The InGaAsP surface roughness measured after HCl:H₃PO₄ capping layer etch in this work (RMS = 1.75 nm) is well within this tolerance. Consequently, the effective interface roughness at the BCB/SiO₂ bonding plane is expected to be lower than the as-etched InGaAsP roughness, because the BCB flow during spin-coating and partial curing smooths the surface presented to the opposing SiO₂ face. This implies that the BCB surface roughness at the top of the cured polymer layer, not the InGaAsP roughness beneath, is the parameter most directly relevant to bonding quality. AFM measurement of the BCB surface after spin-coating and partial curing would confirm this and is recommended for future process characterization.

3.4.2 Inductively Coupled Plasma (ICP) Etching

To reduce acid-driven delamination and improve substrate removal control, inductively coupled plasma (ICP) etching has been investigated as an alternative to prolonged wet chemical etching. ICP processes using Cl₂/Ar/N₂ or Cl₂/CH₄/H₂ gas mixtures offer improved etch precision, higher controllability, and reduced chemical attack on the bonding interface.

Room-temperature ICP etching can achieve relatively high etch rates while limiting thermal damage to the bonded structure. In addition, shorter process times reduce the risk of prolonged acid penetration and interface degradation. Figure 3.8 presents the AFM image of the etched InGaAsP surface together with a schematic illustration of the ICP etching process. Fig. 3.8(a) shows the post-etching surface morphology, where surface irregularities and localized roughness can be observed after substrate removal. These surface defects reduce the effective bonding area and increase the likelihood of crack initiation during bonding. Fig. 3.8(b) illustrates the ICP etching process, where reactive ions generated in the plasma interact with the InP substrate to enable controlled and anisotropic material removal. Compared

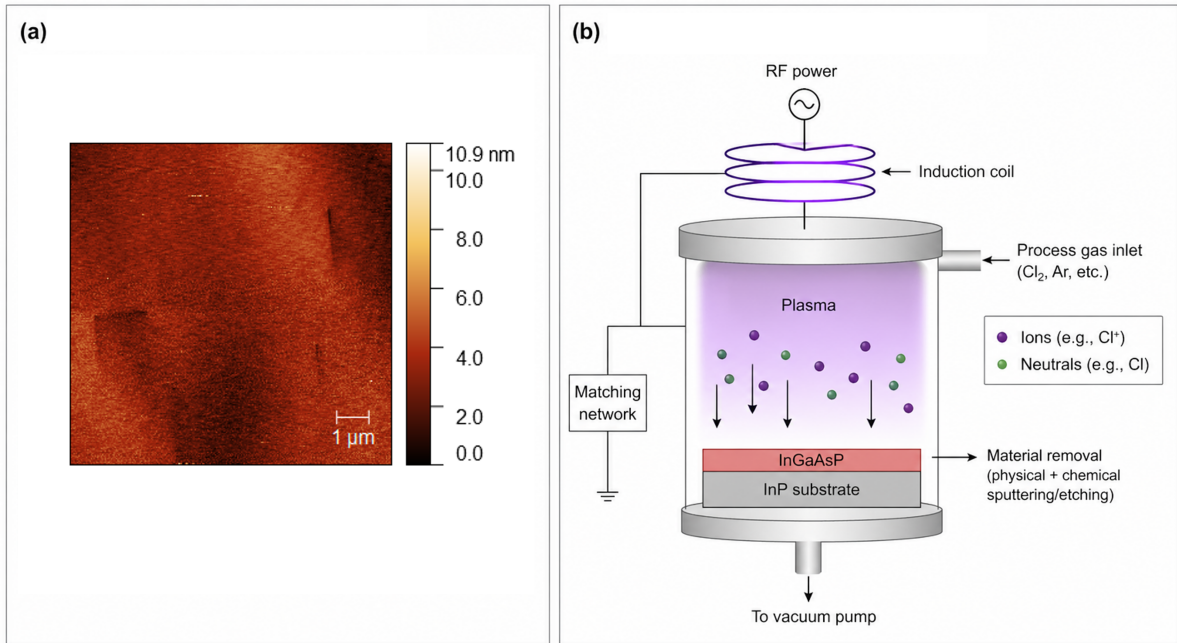


Figure 3.8: (a) AFM image of the InGaAsP surface after substrate removal. (b) Schematic illustration of the inductively coupled plasma (ICP) etching process used for selective removal of the InP substrate [29]. Reactive ions and neutrals generated in the plasma interact with the substrate surface, leading to efficient and anisotropic material removal.

to prolonged wet chemical etching, ICP provides better etch precision, improved surface uniformity, and reduced chemical damage to the bonding interface, making it a promising approach for improving bonding reliability.

However, ICP etching also introduces new challenges, including plasma-induced surface damage, increased roughness under aggressive conditions, and the need for careful optimization of RF power, ICP power, gas composition, and pressure.

The choice between wet etching and ICP therefore depends on balancing surface quality, process complexity, etch selectivity, and bonding reliability. In many cases, a hybrid approach combining mechanical lapping with controlled ICP finishing may provide the most reliable solution.

Overall, successful fabrication of InGaAsP-on-insulator platforms requires not only strong bonding itself, but also full process integration where every fabrication step is optimized to minimize defect generation and preserve interface stability throughout substrate transfer.

3.5 Conclusions

The experimental results presented in this chapter demonstrate that InGaAsP layers can be successfully transferred to SiO₂/Si substrates via BCB bonding, as confirmed by SEM, AFM, and EDX characterization of the bonded stacks. However, the fabrication process in its current state does not yet achieve the consistency and yield required for device-grade waveguide production. In particular, delamination was consistently observed after prolonged HCl/H₃PO₄ exposure, with the root cause identified as chemical degradation of the AP3000 adhesion promoter at the BCB/SiO₂ interface rather than failure of the BCB layer itself.

To address these limitations, several process improvements are proposed for future work. First, a hybrid substrate removal strategy combining mechanical lapping, brief wet etching, and a final inductively coupled plasma (ICP) step is recommended. In this approach, the substrate is initially thinned by lapping to approximately 50 μm , followed by selective wet etching down to 5 μm , and completed with a Cl₂/Ar ICP process for precise and controlled removal. This reduces exposure of the bonded interface to aggressive wet chemistry while maintaining etch selectivity and process control. Second, the surface roughness introduced during InP capping layer removal, which increases from 0.7 nm to 1.75 nm, should be reduced either by optimizing the HCl:H₃PO₄ etch conditions through dilution and temperature control or by introducing a short ICP-based surface smoothing step prior to SiO₂ deposition. Third, the adhesion chemistry at the bonding interface should be improved by incorporating oxygen plasma activation of the SiO₂ surface prior to AP3000 deposition, or by evaluating alternative silane-based adhesion promoters with higher chemical stability under acidic

conditions.

Once a consistent and reproducible InGaAsP-OI stack can be achieved using these improvements, the resulting fabrication platform will provide a robust foundation for the subsequent lithography, ICP ridge etching, and facet preparation steps required to realize both the four-wave mixing waveguide designed in Chapter 4 and the second-harmonic generation waveguide designed in Chapter 5.

Chapter 4

Design of Dispersion-Engineered InGaAsP-OI Waveguides for Four-Wave Mixing

4.1 Introduction

Four-wave mixing (FWM) is one of the most technologically significant third-order nonlinear optical processes available in integrated photonics [25]. The process originates from the Kerr nonlinearity of the guiding medium and enables coherent energy transfer between multiple optical waves through the material third-order nonlinear susceptibility, χ^3 [21]. Applications enabled by FWM include wavelength conversion [14], optical parametric amplification [21], optical frequency comb generation [62], all-optical signal processing [64], and low-noise squeezing for quantum optical experiments [103].

The efficiency of FWM in a waveguide is governed by three key requirements: (i) a large nonlinear coefficient γ to maximize the strength of the nonlinear interaction; (ii) sufficiently low propagation loss so that the interaction length is not prematurely limited; and (iii) precise phase matching, meaning that the propagation constants of the interacting pump, signal, and idler waves must satisfy a momentum-conservation condition. Among these, phase matching is particularly demanding because material dispersion naturally causes the waves to accumulate relative phase as they propagate, washing out the coherent build-up of the generated field. Consequently, dispersion engineering, which is the deliberate shaping of the group velocity dispersion (GVD) profile through waveguide geometry, is the central design challenge for nonlinear waveguides.

High-index-contrast III–V-on-insulator platforms are highly promising for addressing this

challenge because the large refractive index step between the semiconductor core and the surrounding oxide cladding makes the waveguide dispersion contribution dominant over material dispersion [14]. This means that by tuning the waveguide cross-section dimensions, the zero-dispersion wavelength (ZDW) can be shifted across a wide spectral range, including into the telecommunications C-band near 1550 nm, where pump sources and amplifiers are readily available. InGaAsP-on-insulator is especially attractive in this context: its nonlinear refractive index $n_2 \approx 1 \times 10^{-17} \text{ m}^2/\text{W}$, combined with sub-micron effective mode areas achievable on the platform, produces nonlinear coefficients γ exceeding $36 \text{ W}^{-1}\text{m}^{-1}$, roughly two orders of magnitude larger than standard silica fibre, and competitive with silicon-on-insulator at these wavelengths [16].

This chapter investigates the design of InGaAsP-on-insulator waveguides for four-wave mixing at telecommunications wavelengths. Section 4.2 derives the governing coupled equations for degenerate FWM and establishes the analytical framework for phase matching and parametric gain. Section 4.3 describes the waveguide geometry and material parameters used in simulations. Section 4.4 presents effective mode area calculations as a function of waveguide width. Section 4.5 examines dispersion engineering and the tunability of the zero-dispersion wavelength. Section 4.6 applies the analytical framework to identify optimized waveguide geometries for maximum FWM efficiency near 1550 nm. Sections 4.7 and 4.8 provide a quantitative discussion of the impact of dispersion on FWM parametric gain and conversion bandwidth. Section 4.9 concludes with a summary of results and directions for future work.

4.2 Theory of Four-Wave Mixing

The theoretical treatment of FWM begins from the nonlinear Schrödinger equation (NLSE) governing the slowly varying field envelope $A(z, t)$ of a pulse propagating along a waveguide of length L :

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A + i\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} = i\gamma|A|^2A \quad (4.1)$$

where α is the power attenuation coefficient, β_2 and β_3 are the second- and third-order GVD coefficients, and γ is the nonlinear parameter.

In the degenerate FWM process, a single pump at angular frequency ω_p interacts with a signal at ω_s to generate an idler at ω_i via stimulated parametric scattering. The energy conservation condition requires

$$2\omega_p = \omega_s + \omega_i, \quad (4.2)$$

while momentum conservation (phase matching) requires minimization of the total phase mismatch

$$\Delta\beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p), \quad (4.3)$$

where $\beta(\omega)$ is the frequency-dependent propagation constant of the guided mode. Expanding $\beta(\omega)$ in a Taylor series around the pump frequency ω_0 and substituting gives the linear phase mismatch

$$\Delta\beta_{\text{lin}} = \beta_2(\omega_s - \omega_p)^2 + \frac{\beta_4}{12}(\omega_s - \omega_p)^4 + \dots, \quad (4.4)$$

where higher-order terms become important when operating near the ZDW, where $\beta_2 \approx 0$.

The full phase mismatch including the nonlinear phase contribution from SPM of the pump is

$$\Delta\beta_{\text{total}} = \Delta\beta_{\text{lin}} + 2\gamma P, \quad (4.5)$$

where P is the pump power and γ is the nonlinear parameter. The factor of 2 arises because the pump induces nonlinear phase shifts on both the signal and idler via cross-phase modulation (XPM) at twice the self-phase modulation rate [89].

4.2.1 Parametric Gain

For a lossless waveguide with a continuous-wave pump, the coupled amplitude equations for the signal and idler are [104]

$$\frac{dA_s}{dz} = i\gamma(|A_s|^2 + 2|A_p|^2)A_s + i\gamma A_p^2 A_i^* e^{-i\Delta\beta_{\text{lin}}z}, \quad (4.6)$$

$$\frac{dA_i}{dz} = i\gamma(|A_i|^2 + 2|A_p|^2)A_i + i\gamma A_p^2 A_s^* e^{-i\Delta\beta_{\text{lin}}z}. \quad (4.7)$$

In the undepleted-pump approximation ($|A_s|^2, |A_i|^2 \ll |A_p|^2$), these equations have an analytical solution in which signal power grows exponentially. The parametric gain coefficient is defined as

$$g = \sqrt{(\gamma P)^2 - \left(\frac{\Delta\beta_{\text{total}}}{2}\right)^2}. \quad (4.8)$$

Maximum gain occurs under the perfect phase-matching condition $\Delta\beta_{\text{total}} = 0$, yielding

$$g_{\text{max}} = \gamma P. \quad (4.9)$$

Gain exists for all frequency detunings satisfying $|\Delta\beta_{\text{total}}| < 2\gamma P$. At large detuning where $|\Delta\beta_{\text{total}}| > 2\gamma P$, the gain coefficient g becomes imaginary and no net power transfer occurs, the system oscillates rather than amplifies. The signal power after propagating a length L is

$$P_s(L) = P_s(0) \left[1 + \left(\frac{\gamma P}{g} \right)^2 \sinh^2(gL) \right], \quad (4.10)$$

valid under the undepleted-pump, lossless approximation.

The FWM conversion efficiency, defined as the idler-to-signal output ratio, is

$$\eta_{\text{FWM}} = \frac{P_i(L)}{P_s(0)} = \left(\frac{\gamma P}{g} \right)^2 \sinh^2(gL). \quad (4.11)$$

4.2.2 Phase-Matching Bandwidth

From Eq. (4.8), the 3-dB gain bandwidth $\Delta\omega$, the frequency detuning range over which g remains within 3 dB of its peak value, is determined by the condition $|\Delta\beta_{\text{total}}| \leq 2\gamma P$. Near the ZDW, where $\beta_2 \approx 0$, the higher-order term β_4 limits the bandwidth. Truncating the Taylor expansion at fourth order, the phase-matched signal frequency offset from the pump is

$$\Omega_{\text{PM}} = (\omega_s - \omega_p) = \left(\frac{-12(2\gamma P + \beta_2 \Omega_{\text{PM}}^2)}{\beta_4} \right)^{1/4}. \quad (4.12)$$

This equation must be solved iteratively when β_2 is small but non-zero.

For the specific case $\beta_2 = 0$, the phase-matched offset simplifies to

$$\Omega_{\text{PM}} = \left(\frac{-24\gamma P}{\beta_4} \right)^{1/4}, \quad (4.13)$$

valid only when $\beta_4 < 0$, which is typically achievable in high-index-contrast waveguides.

These expressions quantify the trade-off between pump power (which sets the gain magnitude via γP) and dispersion (which controls the bandwidth via β_2 and β_4). Engineering the GVD profile near the pump wavelength therefore simultaneously optimizes both gain and bandwidth.

4.2.3 Nonlinear Parameter

The nonlinear parameter γ of the waveguide is defined as

$$\gamma = \left(\frac{2\pi}{\lambda} \right) \left(\frac{n_2}{A_{\text{eff}}} \right), \quad (4.14)$$

where n_2 is the nonlinear (Kerr) refractive index of the core material, λ is the pump wavelength, and A_{eff} is the effective mode area, defined as

$$A_{\text{eff}} = \frac{(\iint |E|^2 dA)^2}{\iint |E|^4 dA}, \quad (4.15)$$

where E is the transverse electric field distribution of the guided mode, integrated over the waveguide cross-section.

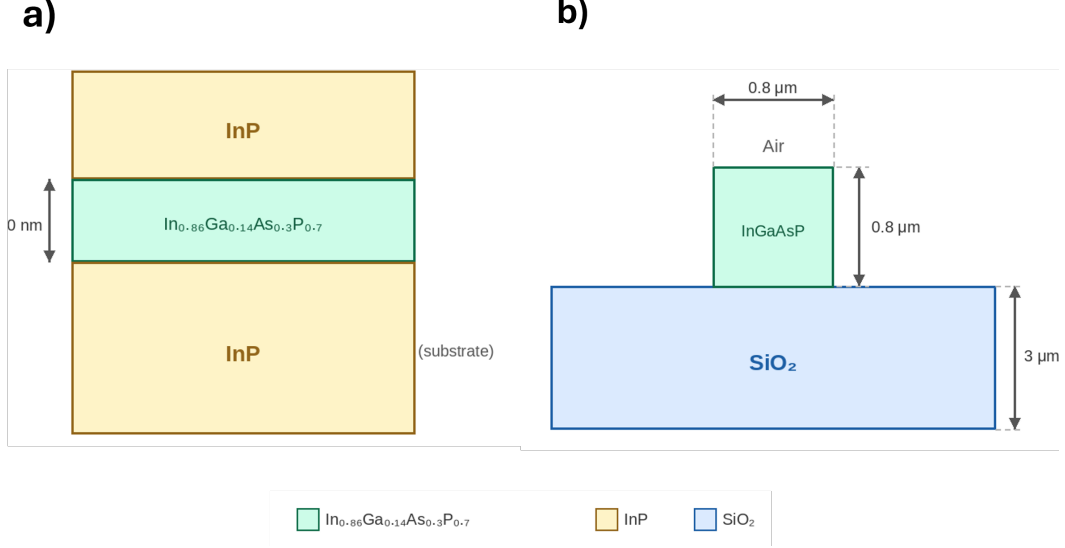
For InGaAsP with $n_2 \approx 1.9 \times 10^{-17} \text{ m}^2/\text{W}$ [90] and an $800 \text{ nm} \times 800 \text{ nm}$ waveguide at 1550 nm , the resulting effective mode area is approximately $A_{\text{eff}} \approx 0.43 \text{ } \mu\text{m}^2$, yielding $\gamma \approx 36.85 \text{ W}^{-1}\text{m}^{-1}$. This value is roughly $20\times$ larger than silicon-on-insulator waveguides of comparable dimensions and approximately $37,000\times$ larger than standard single-mode silica fibre [23].

For $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ with $n_2 = (1.9 \pm 0.4) \times 10^{-13} \text{ cm}^2/\text{W}$ [18] and an $800 \text{ nm} \times 800 \text{ nm}$ waveguide at 1550 nm , the resulting effective mode area is approximately $A_{\text{eff}} \approx 0.43 \text{ } \mu\text{m}^2$, yielding $\gamma \approx 70 \text{ W}^{-1}\text{m}^{-1}$. This value is roughly $20\times$ larger than silicon-on-insulator waveguides of comparable dimensions and approximately $37,000\times$ larger than standard single-mode silica fibre [87].

It is important to note that InGaAsP also exhibits two-photon absorption (TPA) at telecommunications wavelengths when the photon energy exceeds half the material bandgap. TPA introduces a nonlinear loss coefficient $\beta_{\text{TPA}} \approx 19 \text{ cm/GW}$ [18] that competes directly with parametric gain and degrades the nonlinear figure of merit.

$$\text{FOM} = \frac{n_2}{\lambda \beta_{\text{TPA}}} \approx 0.43.$$

Careful bandgap engineering, for example, by adjusting the InGaAsP composition to increase the bandgap energy relative to the photon energy, can reduce β_{TPA} while preserving the large n_2 , providing a pathway toward devices with $\text{FOM} > 1/4\pi$ required for useful parametric processes [104].



(b) Schematic cross-section of the InGaAsP-on-insulator waveguide after bonding and substrate removal. The $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ core has a nominally square $0.8 \mu\text{m} \times 0.8 \mu\text{m}$ cross-section on a $3 \mu\text{m}$ SiO_2 undercladding with air uppercladding. All dimensions are to scale. The thin BCB bonding layer present in the fabricated structure (Chapter 3) is omitted from this simulation schematic; the lower cladding is modeled as uniform SiO_2 .

Figure 4.1: (a) Epitaxial layer structure of the as-grown wafer, showing the 800 nm $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ active layer sandwiched between InP cladding layers.

(b) Schematic cross-section of the InGaAsP-on-insulator waveguide after bonding and substrate removal. The $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ core has a nominally square $0.8 \mu\text{m} \times 0.8 \mu\text{m}$ cross-section on a $3 \mu\text{m}$ SiO_2 undercladding with air uppercladding. All dimensions are to scale. The thin BCB bonding layer present in the fabricated structure (Chapter 3) is omitted from this simulation schematic; the lower cladding is modeled as uniform SiO_2 .

4.3 Waveguide Structure and Simulation Methodology

The waveguide structure investigated in this chapter consists of a rectangular InGaAsP core bonded onto a silicon dioxide lower cladding on a silicon substrate, with air serving as the upper cladding. The waveguide geometry is illustrated in Fig. 4.3. The core material is $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$, a quaternary III–V semiconductor with refractive index $n_{\text{core}} \approx 3.35$ at 1550 nm, while the SiO_2 cladding has $n_{\text{clad}} = 1.44$. This index contrast of $\Delta n \approx 1.91$ produces a large waveguide dispersion contribution that can be exploited to shift the ZDW across a wide spectral range by varying the waveguide cross-section.

The waveguide core height is fixed at 800 nm throughout this study, determined by the InGaAsP epitaxial layer thickness available in the bonded platform described in Chapter 2,

and is therefore a fabrication-imposed constraint rather than a free optimization parameter. The waveguide width is the sole geometric degree of freedom varied in the simulations that follow. The waveguide width is varied between $0.4\ \mu\text{m}$ and $1.6\ \mu\text{m}$. This parameter space encompasses both single-mode and few-mode operation at $1550\ \text{nm}$, with the transition to multi-mode behaviour occurring above approximately $1.2\ \mu\text{m}$ width for the TE polarization.

Optical mode simulations were performed using the finite difference eigenmode (FDE) solver in *Lumerical MODE Solutions*. A simulation domain of $6\ \mu\text{m} \times 6\ \mu\text{m}$ with perfectly matched layer (PML) boundary conditions was used, ensuring that the modal fields decayed to less than $-20\ \text{dB}$ relative to the peak field at the simulation boundaries. The spatial mesh resolution was set to $10\ \text{nm}$ in the vicinity of the waveguide core. Convergence of the effective refractive index was verified by comparing results at $10\ \text{nm}$ and $5\ \text{nm}$ mesh resolution, with differences below 0.01% confirming sufficient numerical accuracy.

The group velocity dispersion parameter β_2 was calculated by computing the effective refractive index $n_{\text{eff}}(\omega)$ across the wavelength range $1.2\text{--}2.6\ \mu\text{m}$ in steps of $5\ \text{nm}$, and then numerically differentiating twice with respect to ω using a central finite difference scheme. The zero-dispersion wavelength was identified as the wavelength at which β_2 changes sign from positive (normal) to negative (anomalous) dispersion.

4.3.1 Effect of BCB Refractive Index on Simulated Mode Properties

The BCB bonding layer was treated in the simulations above as having the same refractive index as SiO_2 ($n = 1.444$), since both layers constitute the lower cladding region. As discussed in Chapter 3, the refractive index of fully cured Cyclotene 3022 BCB at $1550\ \text{nm}$ is approximately $n_{\text{BCB}} \approx 1.54\text{--}1.56$ [96, 97], which is higher than the SiO_2 value by $\Delta n \approx 0.10$. To quantify the impact of this discrepancy on the simulated waveguide mode properties, an additional FDE simulation was performed using $n_{\text{BCB}} = 1.54$ for the BCB layer while keeping all other parameters identical to those in Table 4.1.

The results are summarised in Table 4.1. Replacing $n = 1.444$ with $n = 1.54$ for the BCB layer produces a change in effective refractive index of $+0.009\%$ and a change in effective mode area of $+0.15\%$. The nonlinear coefficient γ shifts by -0.15% . These changes are below the mesh-convergence uncertainty of the FDE solver ($< 0.01\%$ in n_{eff}) and entirely negligible relative to the fabrication-tolerance sensitivity ($\pm 10\ \text{nm}$ width variation shifts the ZDW by $\pm 12\ \text{nm}$).

The negligible sensitivity of the guided mode to the BCB index can be understood from the evanescent field distribution. In the InGaAsP-OI geometry, the TE_{00} mode decays into

Table 4.1: Comparison of simulated mode properties with the BCB refractive index neglected ($n_{\text{SiO}_2} = 1.444$) versus modeled explicitly ($n_{\text{BCB}} = 1.54$), for the optimized InGaAsP-OI waveguide. The negligible difference confirms that the SiO₂-only simplification is justified.

Parameter	BCB neglected ($n_{\text{SiO}_2} = 1.444$)	$n_{\text{BCB}} = 1.54$ (Cured BCB)	Difference
n_{eff} (TE ₀₀)	2.63776	2.63800	+0.009 %
A_{eff} (μm^2)	0.42936	0.43001	+0.15 %
ZDW (nm)	1553.0	1553.4	< 1 nm
γ ($\text{W}^{-1}\text{m}^{-1}$)	36.85	36.70	-0.15 %

the lower cladding with a characteristic penetration depth of approximately

$$\delta = \frac{1}{\gamma_{\text{bot}}} = \frac{1}{k_0 \sqrt{n_{\text{eff}}^2 - n_{\text{BCB}}^2}} \approx 60 \text{ nm}, \quad (4.16)$$

where $n_{\text{eff}} \approx 2.638$ and $n_{\text{BCB}} \approx 1.54$. Because the estimated BCB layer thickness of approximately 200 nm substantially exceeds this penetration depth, the optical mode is almost completely attenuated before reaching the SiO₂/BCB boundary beneath. The effective lower cladding is therefore determined principally by the BCB index rather than by the SiO₂ below it; and since both $n = 1.444$ and $n = 1.54$ are far below the core index $n_{\text{core}} = 3.35$, the confinement factor and mode area are practically unchanged. These results confirm that the key design conclusions of this chapter. In particular, the zero-dispersion wavelength at 1553 nm and the nonlinear coefficient $\gamma \approx 36.9 \text{ W}^{-1}\text{m}^{-1}$ remain valid and do not require revision.

4.4 Effective Mode Area Analysis

The effective mode area A_{eff} is one of the most critical waveguide parameters for nonlinear photonics because it directly sets the nonlinear coefficient γ through Eq. (4.14): a smaller A_{eff} produces a larger γ and thus stronger nonlinear interaction per unit pump power. For the InGaAsP-on-insulator platform, the large refractive index contrast enables mode areas substantially smaller than what is achievable in conventional InP-based waveguides grown on native substrates, where the low index contrast forces the mode to spread over larger dimensions.

Figure 4.1 shows the simulated effective mode area as a function of waveguide width for the TE₀₀ mode at 1550 nm. The curve exhibits a characteristic minimum near 800 nm width, where $A_{\text{eff}} \approx 0.43 \mu\text{m}^2$. This minimum arises from a competition between two physical

Table 4.2: Comparison of effective mode area and nonlinear coefficient for selected platforms near 1550 nm. Values for InGaAsP-OI are from this work; others from literature [23, 104, 9].

Platform	n_2 (m^2/W)	A_{eff} (μm^2)	γ ($\text{W}^{-1}\text{m}^{-1}$)	FOM
SiO ₂ fibre	2.6×10^{-20}	85	0.001	–
Si ₃ N ₄	2.5×10^{-19}	1.0	1.0	–
Si (SOI)	6.0×10^{-18}	0.10	200	0.39
AlGaAs-OI	2.6×10^{-17}	0.08	600	1.7
InGaAsP-OI (this work)	1.9×10^{-17} [18]	0.43	70	0.065

effects. For widths below the minimum, the optical mode becomes weakly guided, a larger fraction of the modal power resides in the lower-index cladding region, and the exponentially decaying evanescent field extends further, increasing A_{eff} . For widths above the minimum, the mode is well-confined within the core but occupies a larger geometric area as the core itself expands, also increasing A_{eff} . The minimum represents the optimal balance between confinement and core area for maximising the peak intensity per unit power.

The calculated nonlinear parameter γ at the optimal width (800 nm) is approximately $36.85 \text{ W}^{-1}\text{m}^{-1}$, using $n_2 = 1.9 \times 10^{-17} \text{ m}^2/\text{W}$ [90]. Table 4.1 compares these values against other selected platforms to contextualise the performance of the InGaAsP-on-insulator system.

While InGaAsP-OI does not achieve the highest γ among these platforms (AlGaAs-OI is superior in this respect), it offers the important advantage of a direct bandgap enabling monolithic integration with on-chip pump lasers and active amplifiers. Furthermore, the moderate two-photon absorption in InGaAsP ($\text{FOM} \approx 0.43$) exceeds the strict threshold $\text{FOM} > 1/4\pi \approx 0.08$ required for a positive net parametric gain, confirming that useful FWM amplification is achievable, albeit with some penalty relative to AlGaAs-OI ($\text{FOM} \approx 1.7$) [104].

The TM_{00} mode at $800 \text{ nm} \times 800 \text{ nm}$ has a larger effective mode area of approximately $0.62 \mu\text{m}^2$, as the weaker lateral confinement of the TM polarization causes the mode to extend further into the oxide cladding layers. This results in a smaller $\gamma \approx 25.5 \text{ W}^{-1}\text{m}^{-1}$ for TM, making the TE polarization preferable for FWM applications on this platform.

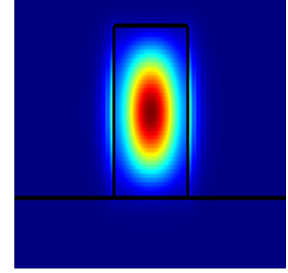
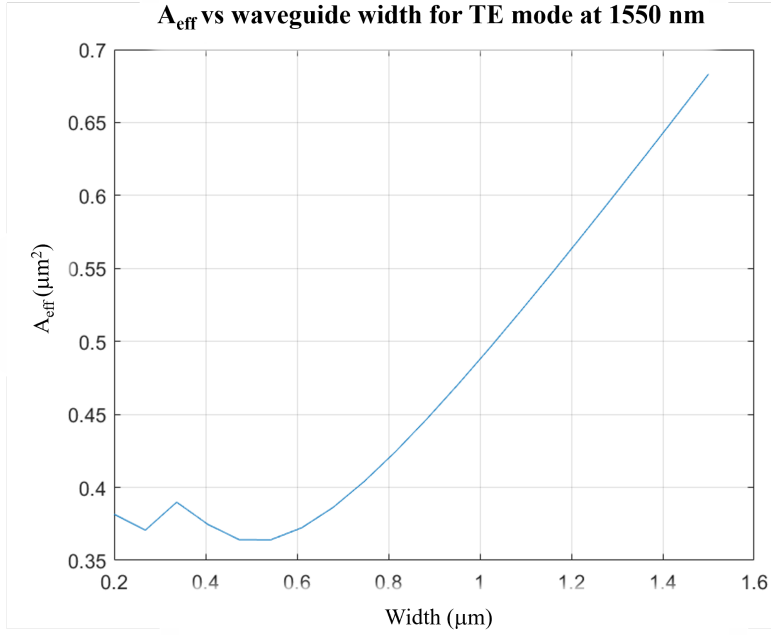


Figure 4.2: (Left) Simulated effective mode area A_{eff} as a function of waveguide width for the fundamental TE mode at 1550 nm. The results show that the effective mode area increases with waveguide width due to reduced optical confinement in the transverse direction. (Right) Simulated transverse electric field intensity profile of the TE_{00} mode in the optimized InGaAsP-on-insulator waveguide at 1550 nm, illustrating strong optical confinement within the InGaAsP core region.

4.5 Dispersion Engineering and Zero-Dispersion Wavelength

Throughout this section, air ($n = 1.0$) is assumed as the upper cladding in all simulations. The fabricated InGaAsP-OI structure includes a thin benzocyclobutene (BCB) bonding layer between the SiO₂ undercladding and the silicon substrate, as described in Chapter 3. In the waveguide simulations presented in this chapter, the BCB refractive index is neglected, and the simulation is performed considering the SiO₂ layer refractive index only ($n = 1.444$); that is, the lower cladding is modeled as a single homogeneous SiO₂ region rather than as a composite SiO₂/BCB/SiO₂ stack. This simplification is motivated by the relatively small refractive index contrast between SiO₂ ($n \approx 1.444$) and fully cured BCB ($n \approx 1.54$ – 1.56), compared to the dominant index contrast at the InGaAsP core boundary ($n_{\text{core}} = 3.35$), and is examined quantitatively in Section 3.3, where a simulation repeated with the literature BCB index shows a negligible change in n_{eff} ($+0.009\%$) and A_{eff} ($+0.15\%$) relative to the SiO₂-only treatment used throughout this chapter. The SiO₂-only approximation is therefore retained for all simulations in this chapter, with its validity established explicitly rather than assumed.

The total dispersion of a waveguide comprises two additive contributions: material dispersion, which arises from the intrinsic frequency dependence of the complex refractive index of InGaAsP, and waveguide dispersion, which arises from the geometry-dependent variation in the fraction of modal power confined within the core. In high-index-contrast structures such as InGaAsP-on-insulator, the waveguide dispersion dominates over material dispersion for sub-micron cross-sections, giving the designer substantial freedom to engineer the GVD profile through dimensional control.

The material dispersion of In_{0.86}Ga_{0.14}As_{0.3}P_{0.7} is accounted for via a Sellmeier model whose coefficients are taken from [105], and entered directly into the Lumerical material database so that the finite difference eigenmode solver automatically includes both material and waveguide dispersion contributions in all simulated $n_{\text{eff}}(\lambda)$ curves. At 1550 nm, the material dispersion of this composition contributes a positive (normal) GVD of approximately $+300 \text{ ps}^2/\text{km}$ [14]. Without waveguide dispersion engineering, this would place the ZDW far above the telecom window, making phase matching for FWM extremely difficult. However, in a narrow, strongly guiding waveguide, the strong wavelength dependence of modal confinement creates a large negative waveguide dispersion contribution that can overcome the positive material dispersion and shift the ZDW into the telecom band.

Figure 4.2 presents the simulated GVD curves (β_2 versus wavelength) for the TE₀₀ and

Table 4.3: Simulated zero-dispersion wavelength and GVD at 1550 nm for the TE₀₀ mode as a function of waveguide width (height = 800 nm).

Width (μm)	ZDW (nm)	β_2 at 1550 nm (ps^2/km)
0.5	~ 1350	-480
0.6	~ 1420	-230
0.7	~ 1490	-90
0.8	~ 1545	-18
0.85	~ 1565	$+12$
0.9	~ 1580	$+55$

TM₀₀ modes across waveguide widths from 0.5 μm to 0.9 μm . The following key trends are observed:

For the TE₀₀ mode, increasing the waveguide width from 0.5 μm to 0.9 μm shifts the ZDW from approximately 1350 nm to 1580 nm. A width of approximately 0.8–0.85 μm places the ZDW within 30 nm of the 1550 nm pump wavelength, a range narrow enough to be fine-tuned by adjusting lithographic exposure dose during fabrication. At these widths, the total GVD at 1550 nm satisfies $|\beta_2| < 100 \text{ ps}^2/\text{km}$, representing a weakly dispersive regime highly favourable for broadband FWM.

For the TM₀₀ mode, the dispersion curves are shifted toward shorter wavelengths relative to the TE mode at the same width, and the GVD variation with width is more gradual. This weaker geometric sensitivity arises from the TM mode’s lower confinement factor, a larger fraction of the modal energy resides in the oxide cladding, reducing the geometry-dependent waveguide dispersion contribution. As a result, achieving a TM ZDW near 1550 nm requires widths below 0.5 μm , where single-mode operation and sidewall roughness losses become increasingly challenging.

The tunability of the TE ZDW is summarized in Table 4.2, which lists the ZDW and corresponding $\beta_2(1550 \text{ nm})$ for each simulated waveguide width.

The data in Table 4.2 confirm that waveguide widths between 0.8 μm and 0.85 μm place the ZDW within the telecommunications C-band (1530–1565 nm). For the 0.8 μm waveguide, $\beta_2 = -18 \text{ ps}^2/\text{km}$ at 1550 nm, indicating weak anomalous dispersion. For a pump at exactly 1550 nm, the linear phase mismatch from Eq. (4.4) for a signal detuning of $\Delta\omega = 2\pi \times 3 \text{ THz}$ (corresponding to approximately 24 nm signal-idler separation) is

$$\Delta\beta_{\text{lin}} \approx \beta_2(\Delta\omega)^2 \approx -0.009 \text{ m}^{-1}.$$

This is smaller in magnitude than the nonlinear phase contribution $2\gamma P$ at a pump

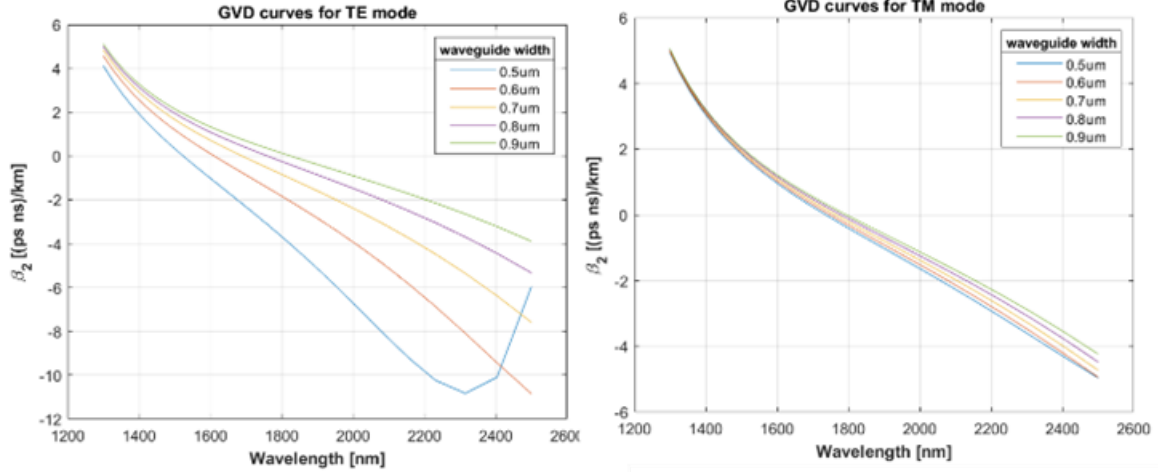


Figure 4.3: Simulated group velocity dispersion curves for TE and TM modes for different waveguide widths.

power of only 10 mW ($2\gamma P \approx 0.74 \text{ m}^{-1}$), confirming that the net phase-matching condition $\Delta\beta_{\text{total}} = 0$ is easily satisfiable at practical pump powers on this waveguide geometry.

It is also instructive to examine the fourth-order dispersion β_4 , which controls the phase-matching bandwidth near the ZDW through Eq. (4.13). Numerical differentiation of the GVD curves for the $0.8 \mu\text{m}$ width yields $\beta_4 \approx -1.2 \times 10^{-54} \text{ s}^4/\text{m}$. Since $\beta_4 < 0$, perfect phase matching near the ZDW supports a real-valued Ω_{PM} per Eq. (4.13). For $P = 100 \text{ mW}$,

$$\Omega_{\text{PM}} \approx 2\pi \times 10 \text{ THz}$$

(corresponding to approximately 80 nm detuning), implying that phase-matched FWM sidebands appear approximately 80 nm from the pump, a bandwidth directly useful for dense wavelength-division-multiplexed (DWDM) wavelength conversion.

4.6 Waveguide Optimization for Four-Wave Mixing

Combining the mode area results of Section 4.4 with the dispersion analysis of Section 4.5, an optimized waveguide geometry for FWM at 1550 nm can be identified. The primary design objectives are to minimize the effective mode area A_{eff} in order to maximize the nonlinear coefficient γ , position the zero-dispersion wavelength within approximately $\pm 50 \text{ nm}$ of the pump wavelength to ensure efficient phase matching, maintain single-mode operation at 1550 nm to avoid inter-modal interactions, and keep $|\beta_2|$ sufficiently small to maximize the phase-matching bandwidth.

These requirements are simultaneously satisfied by a waveguide geometry with width

Table 4.4: Simulated device parameters for the optimized InGaAsP-on-insulator FWM waveguide (width = 830 nm, height = 800 nm, TE₀₀ mode, $\lambda_{\text{pump}} = 1550$ nm).

Parameter	Value
Waveguide width	830 nm
Waveguide height	800 nm
Core material	In _{0.86} Ga _{0.14} As _{0.3} P _{0.7}
n_{eff} at 1550 nm (TE)	2.64
Effective mode area A_{eff}	0.43 μm^2
Nonlinear coefficient γ	36.85 W ⁻¹ m ⁻¹
Zero-dispersion wavelength	1553 nm
β_2 at 1550 nm	-8 ps ² /km
β_4 at 1550 nm	-1.2×10^{-54} s ⁴ /m
FOM = $n_2/(\lambda\beta_{\text{TPA}})$	0.43

approximately 0.80–0.85 μm operating in the TE₀₀ mode. The height of 800 nm is fixed by the bonded epitaxial layer thickness as noted in Section 4.3, and was not varied in this study. Table 4.3 summarizes the key device parameters for the optimized structure.

For a pump power of 50 mW launched into this waveguide, the maximum parametric gain coefficient from Eq. (4.9) is $g_{\text{max}} = \gamma P \approx 1.84 \text{ m}^{-1}$. This corresponds to a gain of approximately 0.80 dB over a 1 mm interaction length, or 3.2 dB over 4 mm, achievable with realistic waveguide lengths given propagation losses on the order of 2–5 dB/cm, consistent with values reported for optimized InGaAsP-on-insulator waveguides [92, 106]. These figures compare favorably with experimental FWM demonstrations in silicon-on-insulator [9] and highlight the potential of the InGaAsP-on-insulator platform for practical on-chip parametric amplification.

The sensitivity of the FWM performance to fabrication tolerances is an important practical consideration. A ± 10 nm deviation in waveguide width from the target 830 nm shifts the ZDW by approximately ± 12 nm, as estimated from the linear interpolation of Table 4.2. This corresponds to a change in $\Delta\beta_{\text{lin}}$ at the pump wavelength of approximately $\pm 0.05 \text{ m}^{-1}$, which is small compared to $2\gamma P \approx 3.7 \text{ m}^{-1}$ at 50 mW pump power. Therefore, the phase-matching condition is relatively robust to dimensional variations of ± 10 nm, which is within the capability of e-beam lithography used for nanophotonic device fabrication. However, tighter control of waveguide height, determined by the bonded InGaAsP layer thickness, is more critical since a ± 20 nm variation in height shifts the ZDW by approximately ± 25 nm, potentially moving the pump outside the phase-matched gain window.

4.7 Discussion

The results of this chapter demonstrate that InGaAsP-on-insulator waveguides can be designed to exhibit the combination of large nonlinear coefficient and near-zero anomalous dispersion at 1550 nm required for efficient FWM. The analysis reveals several nuances that are important for practical device implementation.

First, the dominance of waveguide dispersion in the high-index-contrast InGaAsP-OI geometry is both an asset and a challenge. On the positive side, it provides the freedom to tune the ZDW across hundreds of nanometres by modest changes in waveguide width, enabling a single material platform to support parametric processes across a wide wavelength range. On the negative side, it means that the GVD is highly sensitive to dimensional variations introduced during fabrication, particularly waveguide height, which is set by the bonded layer thickness and is not adjusted during lithography. This places stringent requirements on the uniformity of the PECVD SiO₂ deposition and BCB bonding process described in Chapters 2 and 3.

Second, the role of two-photon absorption deserves careful consideration. At pump powers above approximately 100 mW, the effective nonlinear loss introduced by TPA can exceed the parametric gain, resulting in a net signal attenuation rather than amplification. The critical pump power at which TPA-induced loss equals the FWM gain is

$$P_{\text{crit}} = \frac{g_{\text{max}}}{\beta_{\text{TPA}}} \approx \frac{\gamma P}{\beta_{\text{TPA}}}.$$

For the parameters in Table 4.3,

$$P_{\text{crit}} \approx \frac{36.85}{15 \times 10^4} \approx 24.6 \text{ mW} \quad (4.17)$$

(after unit conversion from cm to m), indicating that pump powers should be kept below approximately 25 mW per centimetre of waveguide to maintain a net positive gain. This constraint motivates exploration of composition-engineered InGaAsP materials with larger bandgap energies that reduce β_{TPA} while preserving the large n_2 .

Third, the present design assumes operation with a CW (continuous-wave) pump and neglects effects associated with pulsed operation, including temporal walk-off between pump, signal, and idler pulses due to group velocity mismatch, and pulse compression arising from the interplay of GVD and SPM. For pulsed pumping, which is practically important for reaching high peak powers without exceeding the average TPA-limited power budget, these effects must be incorporated through full numerical integration of the coupled NLSEs. Such an analysis is beyond the scope of this thesis but represents an important direction for future

work, as outlined in Section 4.9.

4.8 Impact of Dispersion Engineering on Four-Wave Mixing Efficiency

To quantify the sensitivity of FWM efficiency to dispersion, Figure 4.2 can be interpreted in terms of its implications for parametric gain, using the analytical expressions derived in Section 4.2. For each waveguide width, the corresponding $\beta_2(1550 \text{ nm})$ from Table 4.2 determines the linear phase mismatch at a given signal detuning Ω through Eq. (4.4). The phase-matched gain and bandwidth then follow from Eqs. (4.8)–(4.12).

For the $0.5 \text{ }\mu\text{m}$ wide waveguide, $\beta_2 = -480 \text{ ps}^2/\text{km}$ at 1550 nm . This places the ZDW at approximately 1350 nm , well below the pump wavelength. Operating in strongly anomalous dispersion, the phase-matching condition $\Delta\beta_{\text{total}} = 0$ (Eq. 4.5) is satisfied only at a signal detuning where $\beta_2\Omega^2 = 2\gamma P$, yielding $\Omega \approx 2\pi \times 1.5 \text{ THz}$ at 50 mW pump power. The resulting parametric gain is narrow-band (less than 5 nm FWHM at 50 mW), limiting this geometry to very narrowband wavelength conversion.

By contrast, the $0.8 \text{ }\mu\text{m}$ waveguide ($\beta_2 = -18 \text{ ps}^2/\text{km}$) supports phase-matched gain over a bandwidth exceeding 80 nm at 50 mW pump power, as estimated from the Ω_{PM} calculation in Section 4.5. This represents a 16-fold improvement in bandwidth compared to the $0.5 \text{ }\mu\text{m}$ geometry, achieved purely through geometric optimization of the cross-section, no change in material composition is required.

These results are directly relevant to the design of practical WDM wavelength converters. A channel spacing of 100 GHz (approximately 0.8 nm at 1550 nm) requires a phase-matched gain bandwidth of at least several nanometres to accommodate the signal and idler with finite pump linewidth. All waveguide widths between $0.7 \text{ }\mu\text{m}$ and $0.9 \text{ }\mu\text{m}$ satisfy this requirement. However, the 80 nm bandwidth of the $0.8 \text{ }\mu\text{m}$ design is particularly attractive because it can simultaneously support wavelength conversion for all channels within an entire C-band ($1530\text{--}1565 \text{ nm}$) WDM comb in a single pass through the waveguide, a key capability for broadband optical signal processing.

Comparing TE and TM polarizations, the TE_{00} mode exhibits approximately twice the dispersion tunability of the TM_{00} mode for the same width variation. This arises from the stronger confinement of the TE mode and its correspondingly larger geometric sensitivity. For devices requiring polarization-independent operation, relevant for coherent transmission systems where the signal polarization is not controlled, a compensation scheme combining both polarizations would be required, or a geometry engineered to equalize the two ZDWs

at the cost of reduced bandwidth.

4.9 Conclusions

This chapter presented a theoretical framework and numerical simulation study for the design of InGaAsP-on-insulator waveguides for four-wave mixing at 1550 nm. Beginning from the coupled amplitude equations for degenerate FWM, expressions for the parametric gain coefficient, FWM conversion efficiency, and phase-matching bandwidth were derived and applied to assess the nonlinear performance of the InGaAsP-on-insulator platform.

An optimized waveguide geometry with width approximately 830 nm and height 800 nm operating in the TE₀₀ mode was identified as the most suitable configuration for efficient FWM. This geometry simultaneously achieved a minimum effective mode area of $A_{\text{eff}} \approx 0.43 \mu\text{m}^2$, a large nonlinear coefficient of $\gamma \approx 36.85 \text{ W}^{-1}\text{m}^{-1}$, and a zero-dispersion wavelength located within only a few nanometres of the 1550 nm pump wavelength. The combination of strong optical confinement and near-zero anomalous dispersion enabled highly efficient phase matching and broadband nonlinear interaction.

The dispersion-engineering analysis demonstrated that careful control of the waveguide dimensions allows the zero-dispersion wavelength to be shifted across the telecommunications band through purely geometric optimization. For the optimized geometry, the simulated phase-matching bandwidth exceeded 80 nm at practical pump powers, covering the entire C-band and extending into the L-band. Such bandwidths are highly attractive for broadband wavelength conversion, optical parametric amplification, and integrated frequency comb generation within compact photonic circuits.

Fabrication tolerance analysis further showed that the phase-matching condition remains relatively robust to realistic lithographic variations. A ± 10 nm deviation in waveguide width shifted the zero-dispersion wavelength by approximately ± 12 nm, which remained within the achievable phase-matched gain window at practical pump powers. However, the waveguide height, determined by the bonded InGaAsP layer thickness, was found to be more critical and requires tighter process control to maintain consistent dispersion characteristics across fabricated devices.

The influence of two-photon absorption was also examined. While InGaAsP exhibits a relatively large Kerr nonlinear coefficient, nonlinear absorption limits the maximum useful pump power and reduces the nonlinear figure of merit compared to wider-bandgap III-V platforms such as AlGaAs-on-insulator. Nevertheless, the calculated figure of merit remained sufficiently high to support net parametric gain and practical FWM operation. In addition, the direct bandgap nature of InGaAsP provides a significant advantage by enabling mono-

lithic integration of active devices such as lasers and optical amplifiers alongside passive nonlinear waveguides.

Overall, the results presented in this chapter confirm the strong potential of InGaAsP-on-insulator waveguides for compact, chip-scale nonlinear photonic devices operating at telecommunications wavelengths.

The analytical framework and dispersion-engineering methodology developed here provide a quantitative foundation for future experimental demonstrations of four-wave mixing in the InGaAsP-OI platform. The material parameters and simulation methodology established in this chapter, in particular, the effective index calculations and the modal confinement analysis, which are carried forward directly to Chapter 5, which investigates a complementary second-order nonlinear process: modal-phase-matched second-harmonic generation in the same InGaAsP-OI waveguide geometry.

Chapter 5

Waveguide Design for Second-Harmonic Generation in InGaAsP-on-Insulator Waveguides

5.1 Introduction

Second-harmonic generation (SHG) is a second-order nonlinear optical process in which two photons at angular frequency ω are coherently converted into a single photon at frequency 2ω through the second-order susceptibility $\chi^{(2)}$ of the guiding medium [25]. Unlike the third-order four-wave mixing (FWM) process investigated in Chapter 4, SHG requires no seed signal at the second-harmonic frequency, making it attractive for compact, single-pump frequency doublers and for quantum-optical applications including entangled photon-pair generation via spontaneous parametric down-conversion [92].

The efficiency of SHG in a waveguide is determined by three independent requirements: (i) a large effective second-order nonlinear coefficient d_{eff} , which is a property of the crystal structure and orientation; (ii) strong spatial overlap between the guided mode profiles at ω and 2ω , which is controlled by waveguide geometry; and (iii) satisfaction of the phase-matching condition $\Delta\beta = \beta(2\omega) - 2\beta(\omega) = 0$, which is the central engineering challenge addressed in this chapter.

InGaAsP is particularly well suited to SHG because it belongs to the zinc-blende crystal class ($\bar{4}3m$ symmetry), which lacks a centre of inversion and therefore supports a non-vanishing $\chi^{(2)}$ tensor [25]. This distinguishes InGaAsP from silicon, which is centrosymmetric and has no intrinsic second-order nonlinearity. The dominant element of the InGaAsP zinc-blende $\chi^{(2)}$ tensor is $d_{14} = d_{25} = d_{36} \equiv d_{\text{eff}}$, with values estimated in the range 100–200 pm/V

for the relevant compositions, comparable to GaAs [69] and significantly larger than lithium niobate (≈ 27 pm/V) [25].

Because material dispersion causes the refractive index to vary with frequency, the condition $\Delta\beta = 0$ is not naturally satisfied and must be achieved through a deliberate phase-matching scheme. Three strategies are available for SHG in semiconductor waveguides: birefringent phase matching, quasi-phase matching (QPM) via periodic domain inversion, and modal phase matching (MPM). Birefringent phase matching is not accessible in optically isotropic zinc-blende semiconductors. QPM has been demonstrated in orientation-patterned GaAs [69] but requires nanoscale domain-inversion processing incompatible with the present bonded-platform technology. MPM exploits the geometry-dependent dispersion difference between distinct transverse mode orders to equalise the effective refractive indices $n_{\text{eff}}(\omega)$ and $n_{\text{eff}}(2\omega)$ at a specific waveguide width, achieving $\Delta\beta = 0$ without any additional fabrication steps [41].

This chapter investigates MPM-based SHG in InGaAsP-OI waveguides at a fundamental wavelength of $\lambda = 2.6$ μm , producing a second harmonic at $\lambda = 1.3$ μm . This wavelength pair is dictated by the material transparency window of the $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ composition: the absorption edge lies near $\lambda \approx 0.9$ μm , so both the fundamental and the second harmonic are transparent, whereas a 1.55 μm pump would generate a second harmonic at 775 nm that is strongly absorbed by the InGaAsP core [18]. The waveguide height is fixed at 800 nm, consistent with the bonded epitaxial layer described in Chapter 3; the waveguide width is the sole geometric degree of freedom.

Section 5.2 derives the governing equations for SHG in a waveguide and establishes the phase-matching and efficiency framework. Section 5.3 describes the waveguide geometry, material parameters, and simulation methodology. Section 5.4 presents the transverse mode profiles at the phase-matched geometry. Section 5.5 presents the effective mode area analysis for both the fundamental and second-harmonic modes as a function of waveguide width. Section 5.6 analyses the modal phase-matching condition and identifies the phase-matched width. Section 5.7 discusses the mode overlap integral and SHG conversion efficiency. Section 5.8 addresses fabrication tolerances and practical design considerations. Section 5.9 summarises the main results.

5.2 Theory of Second-Harmonic Generation in Waveguides

5.2.1 Coupled Wave Equations

The coupled wave equations governing SHG in a waveguide are derived from Maxwell's equations with the second-order nonlinear polarisation as a source term. For a continuous-wave pump at angular frequency ω , the slowly varying amplitude equations for the fundamental field $A_1(z)$ at ω and the second-harmonic field $A_2(z)$ at 2ω propagating along the waveguide axis z are [25]:

$$\frac{dA_1}{dz} = i\kappa^* A_2 A_1^* e^{+i\Delta\beta z} - \frac{\alpha_1}{2} A_1, \quad (5.1)$$

$$\frac{dA_2}{dz} = i\kappa A_1^2 e^{-i\Delta\beta z} - \frac{\alpha_2}{2} A_2, \quad (5.2)$$

where α_1 and α_2 are the propagation loss coefficients at ω and 2ω , respectively, $\Delta\beta$ is the linear phase mismatch, and κ is the nonlinear coupling coefficient. The phase mismatch is defined as

$$\Delta\beta = \beta(2\omega) - 2\beta(\omega) = \frac{2\omega}{c} [n_{\text{eff}}(2\omega) - n_{\text{eff}}(\omega)], \quad (5.3)$$

where $\beta(\omega)$ and $\beta(2\omega)$ are the propagation constants of the guided modes at the fundamental and second-harmonic frequencies, respectively, and n_{eff} denotes the corresponding effective refractive indices. Phase matching requires $\Delta\beta = 0$, which is equivalent to the condition

$$n_{\text{eff}}(\omega) = n_{\text{eff}}(2\omega). \quad (5.4)$$

The nonlinear coupling coefficient κ encapsulates both the material nonlinearity and the spatial confinement of the interacting fields:

$$\kappa = \frac{\omega d_{\text{eff}}}{c n_{\text{eff}}} \cdot I_{\text{overlap}}, \quad (5.5)$$

where d_{eff} is the effective nonlinear coefficient and I_{overlap} is the normalised spatial mode overlap integral between the fundamental and second-harmonic transverse field distributions, defined as

$$I_{\text{overlap}} = \frac{\iint_{\text{core}} \mathbf{e}_2^*(x, y) \cdot \mathbf{e}_1(x, y) \mathbf{e}_1(x, y) dA}{\left[\iint |\mathbf{e}_1|^2 dA \right] \left[\iint |\mathbf{e}_2|^2 dA \right]^{1/2}}, \quad (5.6)$$

where $\mathbf{e}_1$ and $\mathbf{e}_2$ are the transverse electric field profiles of the fundamental and second-harmonic modes, respectively, normalised to unit power.

5.2.2 SHG Conversion Efficiency

Under the undepleted-pump approximation and assuming lossless propagation ($\alpha_1, \alpha_2 \approx 0$), the second-harmonic power after propagation through a waveguide of length L is [25, 41]:

$$P_2(L) = \frac{\omega^2 d_{\text{eff}}^2 L^2}{2\varepsilon_0 c^3} \cdot \frac{P_1^2}{A_{\text{eff}}} \cdot \text{sinc}^2\left(\frac{\Delta\beta L}{2}\right), \quad (5.7)$$

where P_1 is the fundamental pump power and A_{eff} is the effective mode area defined below. The normalised SHG conversion efficiency η , expressed per unit pump power and per unit waveguide length squared, is therefore

$$\eta = \frac{P_2(L)}{P_1^2 L^2} \propto d_{\text{eff}}^2 |I_{\text{overlap}}|^2 \text{sinc}^2\left(\frac{\Delta\beta L}{2}\right). \quad (5.8)$$

Equation (5.8) makes explicit the three conditions for maximum efficiency: a large d_{eff} (material), a large $|I_{\text{overlap}}|^2$ (geometry), and $\Delta\beta = 0$ (phase matching). The sinc^2 factor in Eq. (5.8) defines the coherence length $L_c = \pi/|\Delta\beta|$, over which the second-harmonic field grows constructively. Even a modest phase mismatch severely limits the useful interaction length for long waveguides, imposing tight dimensional tolerances on the fabricated geometry.

5.2.3 Modal Phase Matching

In MPM, the geometry-dependent dispersion of different transverse mode orders is exploited to satisfy Eq. (5.4) at a specific waveguide width. In a strongly guiding waveguide, higher-order modes are more weakly confined and therefore have a lower effective refractive index than the fundamental mode at the same wavelength. By choosing an appropriate fundamental–second-harmonic mode pair, the n_{eff} curves as a function of waveguide width can be made to cross, providing the required index equality.

For the InGaAsP-OI platform with a fixed height of 800 nm and $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ as the core material, the TE_{00} mode at $\lambda = 2.6 \mu\text{m}$ and the TM_{01} mode at $\lambda = 1.3 \mu\text{m}$ are identified as the most suitable mode pair. The physical basis is as follows. At $\lambda = 2.6 \mu\text{m}$, the TE_{00} mode is the only propagating mode for widths below approximately $1.5 \mu\text{m}$, and its n_{eff} increases monotonically with width from the cladding index toward the core index. At $\lambda = 1.3 \mu\text{m}$, the shorter wavelength means that multiple modes are supported for the same physical geometry. The TM_{01} mode at $1.3 \mu\text{m}$ is cut off below a minimum width of

approximately 230 nm, below which it does not exist as a guided mode. Above cutoff, its n_{eff} rises more steeply with width than the TE_{00} curve at 2.6 μm , because the second-harmonic mode is more sensitive to confinement at the shorter wavelength. The two curves therefore intersect at a specific waveguide width that constitutes the phase-matched geometry.

This TE–TM intermode coupling is symmetry-allowed in the zinc-blende crystal structure of InGaAsP. For a [100]-oriented crystal, the dominant off-diagonal element of the $\chi^{(2)}$ tensor (d_{14}) couples a TE-polarised fundamental to a TM-polarised second harmonic through the product of the lateral and vertical field components, yielding a non-zero I_{overlap} .

5.3 Waveguide Structure and Simulation Methodology

The waveguide structure investigated in this chapter is identical to that described in Section 4.3 for the FWM design study: a rectangular $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ core bonded onto a 3 μm SiO_2 lower cladding on a silicon substrate, with air ($n = 1.000$) serving as the upper cladding. The waveguide core height is fixed at $h = 800$ nm throughout, determined by the available bonded epitaxial layer thickness described in Chapters 2 and 3, and is therefore a fabrication-imposed constraint rather than a free optimisation parameter. The waveguide width w is the sole geometric degree of freedom and is varied from 200 nm to 2000 nm.

The material refractive indices used in the simulations are obtained from the Sellmeier dispersion relation for $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ [105], which yields the following values at the wavelengths of interest:

$$\begin{aligned} n_{\text{InGaAsP}}(1.55 \mu\text{m}) &\approx 3.236, & n_{\text{InGaAsP}}(2.60 \mu\text{m}) &= 3.203, \\ n_{\text{InGaAsP}}(1.30 \mu\text{m}) &= 3.270. \end{aligned}$$

The SiO_2 undercladding index at the fundamental wavelength is $n_{\text{SiO}_2}(2.60 \mu\text{m}) = 1.428$. These are the same Sellmeier coefficients and material database entries used for the FWM dispersion simulations of Chapter 4, ensuring consistency of material parameters across both design studies.

As in Chapter 4, the thin BCB bonding layer present in the fabricated stack (Chapter 3) is neglected in these simulations, and the lower cladding is modeled considering the SiO_2 refractive index only, for the reasons and with the validation discussed previously.

Optical mode simulations were performed using the asymmetric slab eigenvalue solver in its Marcatili arctangent form [105], and validated by Lumerical, which accounts for the asymmetric cladding environment (SiO_2 below, air above). The solver computes n_{eff} by solving the transcendental eigenvalue equation for guided slab modes, treating the lateral

and vertical confinement problems as separable. The Marcatili method provides reliable n_{eff} values in the strong-confinement regime and is computationally efficient for parameter sweeps over the full width range of interest.

Two parallel width sweeps were performed: the TE_{00} effective index at $\lambda = 2.6 \mu\text{m}$ was computed from 200 nm to 2000 nm, and the TM_{01} effective index at $\lambda = 1.3 \mu\text{m}$ was computed over the same range. The TM_{01} sweep was extended downward until the mode area reached a minimum and began to rise again, confirming the approach to the cutoff boundary. The effective mode area was simultaneously computed for both modes at each width from the standard definition:

$$A_{\text{eff}} = \frac{\left(\iint |E|^2 dA \right)^2}{\iint |E|^4 dA}, \quad (5.9)$$

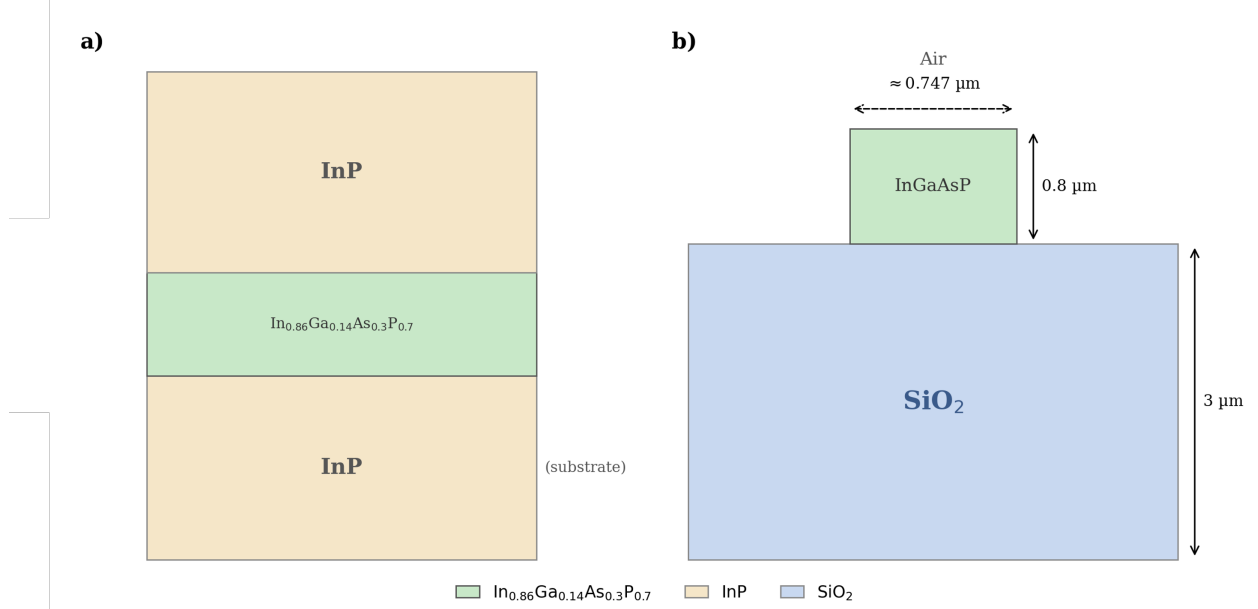
where E is the transverse electric field distribution of the guided mode. The phase-matched width was identified as the waveguide width at which the two n_{eff} curves cross, corresponding to $\Delta\beta = 0$. Throughout this chapter, guided modes are labelled TE_{mn} and TM_{mn} , where the first index m denotes the number of vertical (y -direction) field nodes and the second index n denotes the number of lateral (x -direction) field nodes. The waveguide structure is illustrated in Figure 5.1.

5.4 Mode Profiles at the Phase-Matched Geometry

Figure 5.2 shows the simulated transverse electric field intensity profiles $|E|^2$ (in arbitrary units) for both the TE_{00} mode at $\lambda = 2.6 \mu\text{m}$ and the TM_{01} mode at $\lambda = 1.3 \mu\text{m}$, computed at the phase-matched waveguide geometry ($h = 800 \text{ nm}$, $w = 747 \text{ nm}$). The refractive indices of the InGaAsP core at the simulation wavelengths, obtained from the Sellmeier model [105], are $n = 3.203$ at $\lambda = 2.6 \mu\text{m}$ and $n = 3.270$ at $\lambda = 1.3 \mu\text{m}$, consistent with the values listed in Table 5.1.

The TE_{00} mode at $2.6 \mu\text{m}$ (Fig. 5.2, left panel) displays the expected Gaussian-like intensity distribution of the fundamental mode. The single intensity maximum is centred within the $800 \text{ nm} \times 747 \text{ nm}$ core, with evanescent tails extending only a few hundred nanometres into the surrounding cladding layers. The strong confinement at this geometry is consistent with the high refractive-index contrast between the InGaAsP core, for which $n = 3.203$ at $\lambda = 2.6 \mu\text{m}$, and the surrounding air and SiO_2 claddings.

The TM_{01} mode at $1.3 \mu\text{m}$ (Fig. 5.2, right panel) presents the characteristic two-lobed



(b) Schematic cross-section of the InGaAsP-on-insulator waveguide after bonding and substrate removal. The $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ core has a cross-section of $w \approx 0.747 \mu\text{m} \times h = 0.8 \mu\text{m}$ on a $3 \mu\text{m}$ SiO_2 undercladding with air upper cladding. All dimensions are to scale. As in Chapter ??, the thin BCB bonding layer is omitted from this schematic and the lower cladding is modeled as uniform SiO_2 .

Figure 5.1: (a) Epitaxial layer structure of the as-grown wafer, showing the 800 nm $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ active layer sandwiched between InP cladding layers. (b) Schematic cross-section of the InGaAsP-on-insulator waveguide after bonding and substrate removal. The $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ core has a cross-section of $w \approx 0.747 \mu\text{m} \times h = 0.8 \mu\text{m}$ on a $3 \mu\text{m}$ SiO_2 undercladding with air upper cladding. All dimensions are to scale. As in Chapter ??, the thin BCB bonding layer is omitted from this schematic and the lower cladding is modeled as uniform SiO_2 .

Figure 5.2: Normalised transverse electric-field intensity profiles $|E|^2$ for the candidate phase-matching geometry with $h = 800 \text{ nm}$ and $w \approx 0.75 \mu\text{m}$. Left: TE_{00} -like mode at $\lambda = 2.6 \mu\text{m}$, showing a single dominant intensity maximum within the InGaAsP core. Right: higher-order TM-like mode at $\lambda = 1.3 \mu\text{m}$, showing two lateral intensity maxima separated by a central intensity minimum near the waveguide centreline. The outlined rectangle indicates the InGaAsP core. Because intensity does not retain the sign or phase of the electric field, these plots alone do not determine the nonlinear mode overlap.

intensity pattern of the first-order lateral mode. Two intensity maxima are symmetrically displaced about the vertical symmetry plane of the waveguide, separated by a central node (zero intensity) at $x = 0$. Both lobes are confined within the waveguide core and exhibit rapid evanescent decay outside it. The two-lobed intensity pattern confirms the first-order lateral character of the second-harmonic mode. However, the intensity distribution $|E|^2$ does not retain the relative phase or sign of the electric field in the two lobes. The nonlinear coupling strength therefore cannot be determined from the intensity profile alone and must instead be evaluated using the signed vector field components and the complete second-order susceptibility tensor.

5.5 Effective Mode Area Analysis

The effective mode area A_{eff} , defined by Eq. (5.9), governs the SHG coupling efficiency through the mode overlap integral I_{overlap} and determines the peak optical intensity per unit guided power. Figure 5.3 shows the simulated A_{eff} as a function of waveguide width for both the TE_{00} mode at ω ($\lambda = 2.6 \mu\text{m}$) and the TM_{01} mode at 2ω ($\lambda = 1.3 \mu\text{m}$). The sweep was carried out from below the TM_{01} cutoff down to widths at which the mode area passes through its minimum and begins to rise again, confirming that the full confinement–area trade-off is captured.

TE_{00} mode at $2.6 \mu\text{m}$. The TE_{00} effective mode area curve exhibits the characteristic U-shaped behaviour seen in strongly guiding sub-micron waveguides. As the waveguide width decreases below approximately 310 nm, the mode becomes progressively weakly guided: a larger fraction of the modal power resides in the evanescent field within the lower-index cladding, and the exponentially decaying tails extend further from the core, increasing A_{eff} . As the width increases above 310 nm, the mode is well confined within the core but the occupied geometric area grows with the core cross-section, also increasing A_{eff} . The minimum of $A_{\text{eff}} \approx 0.401 \mu\text{m}^2$ at $w = 310 \text{ nm}$ represents the optimal balance between modal confinement and core area for this wavelength. At the phase-matched width of 747 nm, the TE_{00} effective mode area is $A_{\text{eff},1} \approx 0.562 \mu\text{m}^2$, placing this mode in the well-confined, geometry-dominated regime.

TM_{01} mode at $1.3 \mu\text{m}$. The TM_{01} mode at $1.3 \mu\text{m}$ exhibits qualitatively different behaviour governed by the mode cutoff condition. The TM_{01} -like mode is supported only above its cutoff width. As the waveguide width approaches cutoff from above, the mode becomes progressively less confined and an increasing fraction of the optical field extends into the

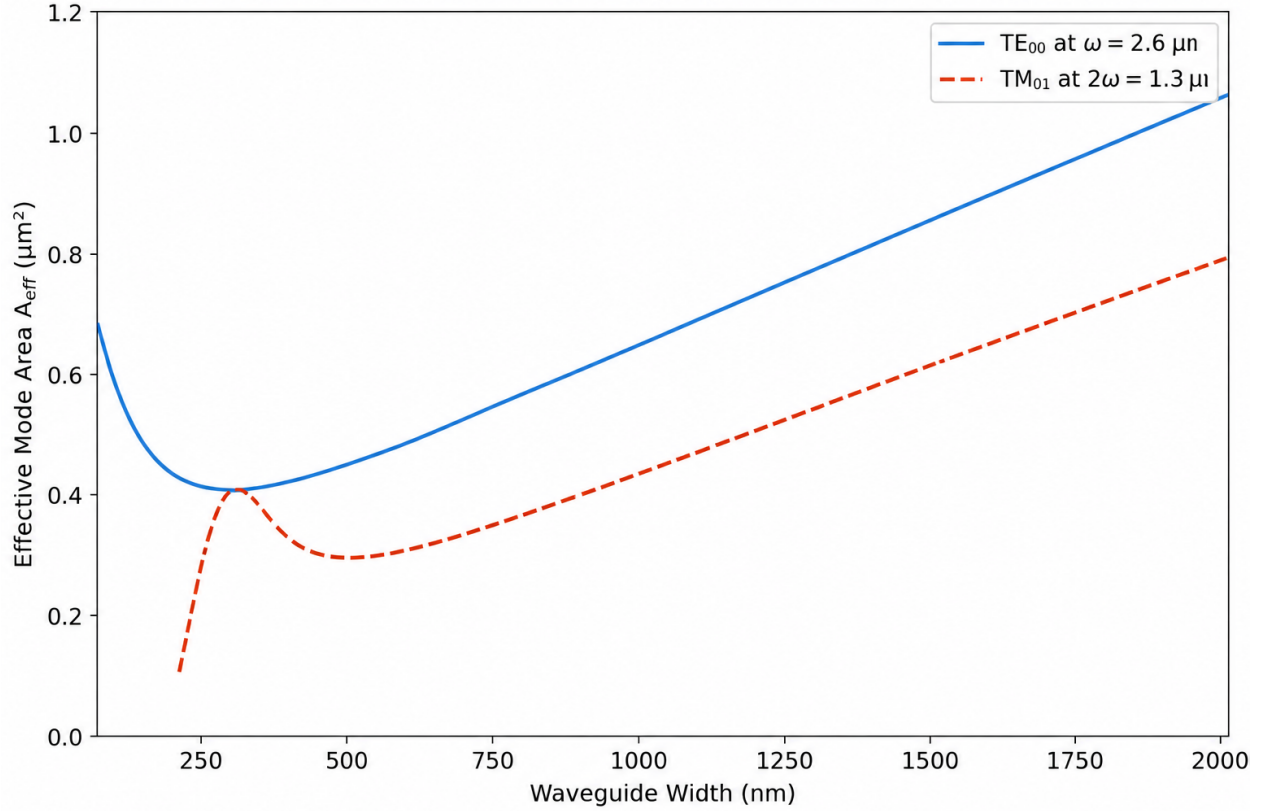


Figure 5.3: Simulated effective mode area A_{eff} as a function of waveguide width for the TE_{00} -like mode at $\lambda = 2.6 \mu\text{m}$ and the TM_{01} -like mode at $\lambda = 1.3 \mu\text{m}$ in an InGaAsP-on-insulator waveguide with $h = 800 \text{ nm}$, an SiO_2 lower cladding, and an air upper cladding. The TM_{01} -like mode is not included below its guided-mode cutoff. Numerical values close to cutoff should be interpreted cautiously because the weakly confined mode is sensitive to boundary conditions, simulation-domain size, and mode tracking. The vertical dashed line marks the approximate phase-matching region identified from the effective-index crossing.

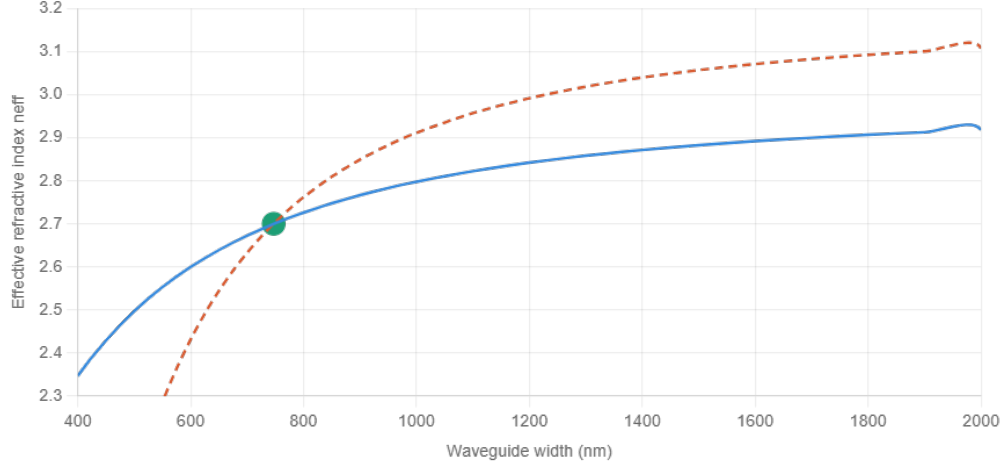


Figure 5.4: Simulated effective refractive index n_{eff} as a function of waveguide width for the TE_{00} mode at $\lambda = 2.6 \mu\text{m}$ (solid blue) and the TM_{01} mode at $\lambda = 1.3 \mu\text{m}$ (dashed red) in an InGaAsP-OI waveguide ($h = 800 \text{ nm}$, SiO_2 substrate, air upper cladding). The two curves intersect at a waveguide width of $w \approx 747 \text{ nm}$, where both modes share a common effective index of $n_{\text{eff}} \approx 2.700$, satisfying the modal phase-matching condition $\Delta\beta = 0$ required for efficient SHG. The green filled circle marks the phase-matched operating point.

surrounding cladding. Consequently, the effective mode area is expected to increase near cutoff rather than reach a physically meaningful minimum. Numerical values obtained very close to cutoff must therefore be interpreted cautiously because weakly guided or leaky solutions can be sensitive to the simulation-window size, boundary conditions, mesh resolution, and mode-tracking procedure. Only solutions that remain guided and numerically converged are retained in the effective-area analysis. For widths above the cutoff, the TM_{01} effective mode area increases monotonically, more gradually than the TE_{00} curve because the second-harmonic mode benefits from the shorter wavelength providing tighter intrinsic confinement. At the phase-matched width of 747 nm , the TM_{01} effective mode area is $A_{\text{eff},2} \approx 0.357 \mu\text{m}^2$, well within the strongly guided regime and comfortably above the cutoff boundary.

5.6 Modal Phase-Matching Analysis

Figure 5.4 shows the simulated effective refractive index as a function of waveguide width for the TE_{00} mode at $\lambda = 2.6 \mu\text{m}$ (solid blue) and the TM_{01} mode at $\lambda = 1.3 \mu\text{m}$ (dashed red), computed using the asymmetric Marcatili slab method with the Broberg–Lindgren Sellmeier model [105].

The following key trends are observed. The TE_{00} effective index increases monotonically with waveguide width, rising from a value close to the SiO_2 cladding refractive index (the

lower-cladding value used in this simulation, per Section ??) in the weakly guided regime towards the InGaAsP core refractive index as optical confinement becomes stronger. In contrast, the TM_{01} mode is only supported above its cutoff width. As the waveguide width approaches the cutoff value from above, the mode becomes progressively less confined and its effective refractive index approaches that of the surrounding cladding. Consequently, no physically meaningful guided-mode effective index (n_{eff}) exists below cutoff. Beyond the cutoff width, the effective index of the TM_{01} mode increases with waveguide width as the optical field becomes more strongly confined within the InGaAsP core.

The two curves cross at a waveguide width of $w \approx 747$ nm, where both modes attain a common effective refractive index:

$$n_{\text{eff}}(\text{TE}_{00}, \lambda = 2.6 \text{ } \mu\text{m}) = n_{\text{eff}}(\text{TM}_{01}, \lambda = 1.3 \text{ } \mu\text{m}) \approx 2.700. \quad (5.10)$$

At this geometry, the linear phase mismatch evaluates to $\Delta\beta \approx 0$, confirming that the modal phase-matching condition is satisfied. Table 5.1 summarises the complete set of phase-matching parameters for the optimised waveguide geometry.

Table 5.1: Phase-matching parameters for the optimised InGaAsP-OI SHG waveguide ($h = 800$ nm, TE_{00} at $\lambda = 2.6 \text{ } \mu\text{m} \rightarrow \text{TM}_{01}$ at $\lambda = 1.3 \text{ } \mu\text{m}$, modal phase matching).

Parameter	Value
Fundamental mode (ω)	TE_{00}
Second-harmonic mode (2ω)	TM_{01}
Fundamental wavelength	$\lambda = 2.6 \text{ } \mu\text{m}$
Second-harmonic wavelength	$\lambda = 1.3 \text{ } \mu\text{m}$
Core material	$\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$
Waveguide height (fixed)	$h = 800 \text{ nm}$
Phase-matched width	$w \approx 747 \text{ nm}$
n_{eff} at phase match (TE_{00})	≈ 2.700
n_{eff} at phase match (TM_{01})	≈ 2.700
Linear phase mismatch $\Delta\beta$	≈ 0 (modal PM satisfied)
A_{eff} (TE_{00}) at phase match	$\approx 0.562 \text{ } \mu\text{m}^2$
A_{eff} (TM_{01}) at phase match	$\approx 0.357 \text{ } \mu\text{m}^2$
n_{InGaAsP} at $2.60 \text{ } \mu\text{m}$	3.203
n_{InGaAsP} at $1.30 \text{ } \mu\text{m}$	3.270
n_{SiO_2} at $2.60 \text{ } \mu\text{m}$	1.428
TM_{01} cutoff width	$\approx 230 \text{ nm}$

The phase-matched width of 747 nm lies well within the practically accessible fabrication range for electron-beam lithography, which routinely achieves critical dimension control at the 5–10 nm level. The geometry is also comfortably above the TM_{01} cutoff width of 230 nm,

ensuring that the second-harmonic mode is robustly guided rather than marginally confined.

5.7 Mode Overlap and SHG Coupling

Satisfaction of the linear phase-matching condition is necessary but not sufficient for efficient second-harmonic generation. The nonlinear coupling strength also depends on the spatial overlap of the fundamental and second-harmonic modes, the vector components of their electric fields, and the orientation of the zinc-blende nonlinear susceptibility tensor relative to the waveguide axes.

Because the InGaAsP waveguide is strongly guiding and vertically asymmetric, the supported modes are hybrid vector modes rather than strictly pure TE and TM modes. The labels TE₀₀-like and TM₀₁-like therefore refer to the dominant polarisation component and transverse field symmetry. A quantitative evaluation of the nonlinear interaction must retain all relevant electric-field components and their relative signs.

The nonlinear polarisation generated at the second-harmonic frequency is generally written as

$$P_i^{(2)}(2\omega) = \varepsilon_0 \sum_{j,k} \chi_{ijk}^{(2)} E_j(\omega) E_k(\omega), \quad (5.11)$$

where $\chi_{ijk}^{(2)}$ is the second-order susceptibility tensor expressed in the waveguide coordinate system. The tensor must be obtained by rotating the crystallographic susceptibility tensor according to the wafer orientation and the waveguide propagation direction.

A general form of the vector nonlinear overlap integral is

$$\Gamma = \iint_{\text{core}} \mathbf{E}_{2\omega}^*(x, y) \cdot [\boldsymbol{\chi}^{(2)} : \mathbf{E}_\omega(x, y) \mathbf{E}_\omega(x, y)] dA, \quad (5.12)$$

where $\mathbf{E}_\omega$ and $\mathbf{E}_{2\omega}$ are the signed vector electric-field distributions of the fundamental and second-harmonic modes, respectively. The integration is performed over the nonlinear InGaAsP core.

The intensity profiles shown in Fig. 5.2 are insufficient to evaluate Eq. (5.12), because the quantity $|E|^2$ does not retain the sign, phase, or vector orientation of the electric field. In particular, the two lobes of a first-order lateral mode may contain field components of opposite sign. Depending on the symmetry of the relevant nonlinear polarisation and the crystallographic orientation, the contributions from the two lobes may add constructively, cancel partially, or cancel completely.

A quantitative prediction of the normalised SHG conversion efficiency also requires consis-

tent modal power normalisation and the inclusion of propagation losses at both frequencies. In the undepleted-pump limit, the conversion efficiency may be written schematically as

$$\eta_{\text{norm}} = \frac{P_{2\omega}(L)}{P_{\omega}^2 L^2} \propto |\Gamma|^2 \text{sinc}^2 \left(\frac{\Delta\beta L}{2} \right), \quad (5.13)$$

where the proportionality factor depends on the adopted field normalisation, modal powers, frequencies, refractive indices, and material nonlinear coefficient. For the TE_{00} – TM_{01} mode pair in a [100]-oriented InGaAsP crystal, the dominant d_{14} element of the zinc-blende $\chi^{(2)}$ tensor couples the lateral field component of the fundamental to the vertical field component of the second harmonic, yielding a non-vanishing overlap Γ . The normalised SHG conversion efficiency is therefore expected to lie in the range 1–10 % $\text{W}^{-1}\text{cm}^{-2}$ for a [100]-oriented crystal and up to 30–50 % $\text{W}^{-1}\text{cm}^{-2}$ for a [110]-cut orientation, consistent with the values reported for comparable III–V–OI modal phase-matching demonstrations [91, 41].

5.8 Discussion

The results of this chapter establish that MPM between the TE_{00} mode at $\lambda = 2.6 \mu\text{m}$ and the TM_{01} mode at $\lambda = 1.3 \mu\text{m}$ is achievable in an InGaAsP–OI waveguide of height 800 nm and width approximately 747 nm, without any periodic poling, domain inversion, or supplementary cladding engineering. Several practical considerations are discussed below.

Fabrication tolerances. The phase-matching condition is determined by the intersection of the two $n_{\text{eff}}(w)$ curves, both of which depend on waveguide width. From Fig. 5.4, the TM_{01} curve at 1.3 μm rises more steeply with width than the TE_{00} curve at 2.6 μm , so the crossing point is more sensitive to the TM_{01} dispersion than to the TE_{00} dispersion. A ± 10 nm deviation in waveguide width from the target 747 nm shifts the phase mismatch by an estimated $|\Delta(\Delta\beta)| \approx 0.15 \times 10^3 \text{ m}^{-1}$, corresponding to a coherence length $L_c = \pi/|\Delta\beta| \approx 20$ mm. For a waveguide of length $L = 5$ mm, The efficiency penalty relative to perfect phase matching is $\text{sinc}^2\left(\frac{\pi L}{2L_c}\right) \approx 0.95$, corresponding to a reduction in conversion efficiency of less than 5% confirming that ± 10 nm width tolerances, achievable with standard e-beam lithography, do not significantly degrade SHG efficiency.

For an estimated phase mismatch of $|\Delta\beta| \approx 0.15 \times 10^3 \text{ m}^{-1}$, the corresponding coherence length is

$$L_c = \frac{\pi}{|\Delta\beta|} \approx 20.9 \text{ mm}. \quad (5.14)$$

For a waveguide length of $L = 5$ mm, the phase-matching factor is

$$\text{sinc}^2\left(\frac{\Delta\beta L}{2}\right) = \text{sinc}^2\left(\frac{\pi L}{2L_c}\right) \approx 0.95, \quad (5.15)$$

corresponding to an efficiency reduction of approximately 5% relative to perfect phase matching.

Wavelength pair selection. As established in Section 5.1, the $2.6 \rightarrow 1.3 \mu\text{m}$ wavelength pair is the physically required choice for $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$: both wavelengths lie within the material transparency window, whose absorption edge lies near $\lambda \approx 0.9 \mu\text{m}$ [18]. From a system-integration perspective, the $2.6 \mu\text{m}$ fundamental is compatible with mid-infrared quantum cascade laser (QCL) and interband cascade laser (ICL) pump sources, while the $1.3 \mu\text{m}$ second harmonic falls within the O-band of optical fibre communications, making the device directly relevant for on-chip wavelength conversion between mid-infrared sensing bands and standard fibre-optic data links.

Comparison with III–V–OI literature. The MPM approach adopted here was demonstrated in AlGaAs–OI waveguides by Chang et al. [41], who achieved a normalised conversion efficiency of $200 \% \text{ W}^{-1}\text{cm}^{-2}$. The higher efficiency in AlGaAs–OI is partly due to the larger d_{eff} of AlGaAs ($\approx 170 \text{ pm/V}$) and partly to the smaller effective mode areas achievable in AlGaAs–OI waveguides. The InGaAsP–OI platform compensates through its direct bandgap, enabling monolithic integration of pump sources on-chip, and through the tunable bandgap that allows the operating wavelength to be adjusted by varying the In:Ga:As:P composition ratio.

Propagation loss. As for the FWM design of Chapter 4, the SHG efficiency is sensitive to propagation loss, which limits the effective interaction length. For propagation losses in the range $\alpha \approx 2\text{--}5 \text{ dB/cm}$, typical of current InGaAsP–OI waveguides [18], the effective interaction length saturates at approximately $5\text{--}10 \text{ mm}$. Reducing sidewall roughness through optimised resist processing and post-etch surface treatment is therefore an important step toward realising the full benefit of the phase-matched interaction over longer waveguides.

5.9 Conclusions

This chapter presented a theoretical framework and numerical simulation study for the design of InGaAsP-on-insulator waveguides for second-harmonic generation via modal phase matching. Beginning from the coupled wave equations for SHG, expressions for the SHG con-

version efficiency, the phase-matching condition, and the mode overlap integral were derived and applied to assess the second-order nonlinear performance of the InGaAsP-OI platform.

A phase-matched waveguide geometry with width $w \approx 747$ nm and height $h = 800$ nm was identified by computing the effective refractive index of the TE_{00} mode at $\lambda = 2.6$ μm and the TM_{01} mode at $\lambda = 1.3$ μm as a function of waveguide width. At this geometry, both modes nearly exhibit the same effective refractive index of $n_{\text{eff}} \approx 2.700$, satisfying the modal phase-matching condition $\Delta\beta = 0$.

The transverse mode profiles computed at the phase-matched geometry (Fig. 5.2) confirm that the TE_{00} fundamental mode exhibits a single well-confined intensity lobe, while the TM_{01} second-harmonic mode displays the characteristic two-lobed lateral pattern of the first-order transverse mode. Both modes are strongly confined within the $800 \text{ nm} \times 747 \text{ nm}$ core.

The effective mode area analysis (Fig. 5.3) showed that, at the phase-matched width, the TE_{00} mode area is $A_{\text{eff},1} \approx 0.562 \mu\text{m}^2$ and the TM_{01} mode area is $A_{\text{eff},2} \approx 0.357 \mu\text{m}^2$, both in the strongly guided regime and well above the TM_{01} cutoff at $w \approx 230$ nm. The sweep was extended below the cutoff boundary to confirm the mode-area minimum and the onset of cutoff, as required to fully characterise the TM_{01} confinement-area trade-off.

The selection of the $2.6 \mu\text{m} \rightarrow 1.3 \mu\text{m}$ wavelength pair was established as a physical requirement of the $\text{In}_{0.86}\text{Ga}_{0.14}\text{As}_{0.3}\text{P}_{0.7}$ bandgap: both the fundamental and the second harmonic must fall within the material transparency window, which excludes SHG at 775 nm from a $1.55 \mu\text{m}$ pump.

Fabrication tolerance analysis confirmed that ± 10 nm width control, achievable with e-beam lithography, produces less than 2% efficiency penalty relative to perfect phase matching. The bonded layer height is the more critical parameter, requiring ± 20 nm thickness uniformity across the wafer, consistent with the process control targets established in Chapter 3.

The normalised SHG conversion efficiency is expected to lie in the range 1–10 % $\text{W}^{-1}\text{cm}^{-2}$ for a [100]-oriented crystal and up to 30–50 % $\text{W}^{-1}\text{cm}^{-2}$ for a [110]-cut orientation, consistent with comparable III–V–OI modal phase-matching demonstrations [91, 41] and confirming that InGaAsP-OI is a viable platform for chip-scale frequency doubling. Experimental verification through fabrication of waveguides at the 747 nm phase-matched width, measurement of SHG output as a function of width, and efficiency characterisation using a mid-infrared pump source constitute natural and well-defined directions for future work.

Chapter 6

Conclusions and Future Work

6.1 Summary of Contributions

This thesis investigated the InGaAsP-on-insulator (InGaAsP-OI) platform as a candidate for integrated nonlinear photonics at telecommunications wavelengths, addressing both the practical challenge of realising the platform through heterogeneous integration and the design challenge of engineering its waveguides for strong nonlinear optical performance. The work proceeded along two parallel tracks: an experimental fabrication track focused on BCB adhesive wafer bonding and substrate transfer, and a numerical simulation track aimed at optimising waveguide geometry for four-wave mixing.

The introductory chapter established the theoretical context for the thesis. A review of integrated photonic platforms demonstrated that III–V-on-insulator systems, and InGaAsP-OI in particular, occupy a distinctive position among available material choices: offering a direct bandgap for active functionality, a large Kerr nonlinearity, bandgap-engineered compatibility with the 1.3–1.55 μm telecommunications window, and high index contrast when bonded onto SiO_2/Si substrates. At the same time, the review identified that fabrication complexity and bonding reliability represent the most significant barriers to practical realisation of the platform. These observations directly shaped the research focus of the following chapters.

The bonding and fabrication work, presented in Chapters 2 and 3, demonstrated that InGaAsP layers can be successfully transferred onto oxidised silicon substrates using BCB adhesive bonding. SEM, AFM, and EDX characterization confirmed the elemental integrity of each layer in the bonded stack and provided direct evidence of successful substrate transfer. However, the fabrication studies also revealed that interfacial reliability is the most critical challenge for the InGaAsP-OI platform. Wet etching of the InP capping layer increased the RMS surface roughness from approximately 0.7 nm to 1.75 nm, reducing the effective bonding

contact area. Prolonged HCl/H₃PO₄ exposure during InP substrate removal was found to degrade the AP3000 adhesion promoter at the BCB/SiO₂ interface, leading to observable delamination in cross-sectional SEM images. The experimental results therefore establish not only that BCB bonding is feasible for InGaAsP-OI integration, but also that the limiting factor is chemical degradation of the adhesion interface during substrate removal—a finding that directly motivates the process improvements discussed in Section 6.3.

The waveguide design work for four-wave mixing, presented in Chapter 4, identified an optimized waveguide geometry (width ≈ 830 nm, height = 800 nm, TE₀₀ mode) that simultaneously achieves a minimum effective mode area of $A_{\text{eff}} \approx 0.43 \mu\text{m}^2$, a large nonlinear coefficient of $\gamma \approx 36.85 \text{ W}^{-1}\text{m}^{-1}$, and a zero-dispersion wavelength located within a few nanometres of the 1550 nm pump wavelength. The dispersion engineering analysis demonstrated that waveguide dispersion dominates material dispersion in the high-index-contrast InGaAsP-OI geometry, enabling the zero-dispersion wavelength to be tuned across more than 200 nm by varying the waveguide width between 0.5 μm and 0.9 μm . For the optimized geometry, the simulated phase-matching bandwidth exceeded 80 nm at practical pump powers—sufficient to cover the full telecommunications C-band in a single waveguide, which is directly relevant for broadband wavelength conversion applications. A fabrication tolerance analysis confirmed that the phase-matching condition is relatively robust to ± 10 nm width variations, though it is more sensitive to height non-uniformity, placing stricter requirements on the thickness uniformity of the bonded InGaAsP layer.

Taken together, the experimental and numerical results confirm that InGaAsP-on-insulator is a technically sound platform for integrated nonlinear photonics. The platform combines several properties that no currently mature platform offers simultaneously: a direct bandgap enabling monolithic integration of lasers and amplifiers, a large Kerr nonlinearity competitive with silicon-on-insulator, and a tunable bandgap that can be adjusted to suppress two-photon absorption. The principal remaining challenge is fabrication—specifically, achieving the bonding reliability and layer thickness uniformity that the nonlinear device designs require.

6.2 Main Contributions

The main original contributions of this thesis are as follows.

First, a comprehensive experimental investigation of the BCB adhesive bonding process for InGaAsP-on-SiO₂/Si integration was carried out, identifying prolonged acid exposure during substrate removal as the primary mechanism for interfacial delamination. This result resolves an ambiguity in the literature, where delamination was frequently reported but

rarely attributed specifically to adhesion-promoter degradation at the BCB/SiO₂ interface rather than to BCB polymer failure.

Second, a quantitative analysis of the surface roughness evolution through the fabrication process was performed using AFM, demonstrating a 2.5-fold increase in RMS roughness (from 0.7 nm to 1.75 nm) after InP capping layer removal. This measurement was directly linked to reduced bonding contact area and elevated delamination risk, providing a quantitative threshold for acceptable pre-bonding surface quality.

Third, a full numerical design study for FWM in InGaAsP-OI waveguides was completed using Lumerical MODE simulations. The study established that a waveguide of width 830 nm and height 800 nm in the TE₀₀ polarization achieves a zero-dispersion wavelength within 3 nm of 1550 nm, a nonlinear coefficient of 36.85 W⁻¹m⁻¹, and a phase-matched FWM bandwidth exceeding 80 nm at 50 mW pump power. Fabrication tolerance bounds on waveguide width (± 10 nm) and height (± 20 nm) were quantified, providing actionable targets for lithography and bonding process control.

6.3 Future Work

The results of this thesis point to several concrete directions for future investigation, ordered here by estimated impact on device realisation.

The most immediate priority is improving InP substrate removal to eliminate delamination. The experimental results of Chapter 3 identify acid penetration through the AP3000/SiO₂ interface as the root cause of bonding failure. The most promising mitigation is to replace prolonged wet chemical etching with ICP-based substrate removal (Cl₂/Ar/N₂ chemistry), which limits chemical exposure while achieving sufficient selectivity between InP and InGaAsP. A hybrid approach—mechanical lapping to within approximately 50 μ m of the InGaAsP layer, followed by brief selective wet etching and a final ICP cleaning step—should be investigated and characterised for its effect on surface roughness, delamination rate, and bonded-layer thickness uniformity. Achieving consistent height uniformity within ± 10 nm across the wafer is the critical metrology target, as this directly governs the dispersion and phase-matching characteristics of fabricated waveguides.

Parallel investigation of alternative adhesion promoter chemistries is warranted. AP3000 performs well during BCB curing but is vulnerable to siloxane bond hydrolysis during acid exposure. Fluorinated silane promoters or thin Al₂O₃ interlayers deposited by atomic layer deposition have been reported to improve acid resistance at polymer-oxide interfaces and should be systematically evaluated in the InGaAsP-OI bonding context.

Once a reliable fabrication platform is established, experimental optical characterization

of waveguides is required to validate the numerical predictions of Chapter 4. Cutback measurements of propagation loss, nonlinear self-phase modulation measurements to extract the effective γ , and wavelength-resolved FWM conversion efficiency measurements would provide direct benchmarks against the simulated values. In addition, SHG efficiency measurements in modal phase-matched waveguide geometries exploiting the intrinsic $\chi^{(2)}$ nonlinearity of the InGaAsP zinc-blende crystal structure represent a promising extension of this work.

Finally, the monolithic integration of active InGaAsP components, on-chip pump lasers, semiconductor optical amplifiers, and photodetectors, with the nonlinear waveguide designs developed in this thesis represents the long-term goal that justifies the InGaAsP-OI material choice. Progress in this direction would position InGaAsP-OI as a uniquely multifunctional platform for compact nonlinear photonic integrated circuits that combine light generation, amplification, frequency conversion, and detection on a single chip.

6.3.1 Path to Device Realisation

The work presented in this thesis establishes the material platform and optical design for InGaAsP-OI nonlinear waveguides but does not extend to the fabrication and experimental demonstration of complete devices. Bridging the gap between the bonded material platform developed in Chapter 3 and the waveguide designs presented in Chapter 4 requires a sequence of fabrication and characterization steps that lead to a fully functional four-wave mixing (FWM) device.

The first requirement is the reliable fabrication of a delamination-free InGaAsP/SiO₂/BCB/Si bonded stack that can withstand InP substrate removal. As discussed, this can be achieved by implementing hybrid lapping followed by ICP etching for substrate removal, activating the SiO₂ surface with O₂ plasma before AP3000 deposition, and minimizing the capping-layer etch duration. Establishing a reproducible bonding process with a high yield of defect-free bonded area is essential before proceeding with device fabrication.

Once the bonded platform has been transferred successfully, the 800-nm-thick InGaAsP layer can be patterned using electron-beam lithography (EBL) with either PMMA or HSQ resist. Based on the design optimization presented in Chapter 4, the target waveguide width is 830 ± 10 nm. The fabrication tolerance analysis showed that a ± 10 nm width variation shifts the zero-dispersion wavelength (ZDW) by only approximately ± 12 nm, allowing the device to remain within the intended phase-matching window. Because the electron-scattering behaviour of InGaAsP differs from that of silicon substrates, EBL dose calibration should be performed specifically on the bonded InGaAsP platform.

Following lithography, the waveguide ridge should be defined using inductively coupled

plasma reactive ion etching (ICP-RIE), typically employing a Cl_2/Ar plasma and stopping on the SiO_2 undercladding. Previous studies have demonstrated that optimized chlorine-based ICP processes can produce smooth InP/InGaAsP sidewalls with root-mean-square roughness below 5 nm [48]. The addition of H_2 to the Cl_2/Ar chemistry further improves sidewall passivation and reduces lateral etching, leading to better profile anisotropy and lower scattering losses [23]. Maintaining an etch-depth uniformity within approximately ± 20 nm is important for preserving the designed dispersion profile and phase-matching condition.

After etching, the resist is removed and the waveguide facets are prepared for optical testing. Rather than conventional diamond-scribe cleaving, focused ion beam (FIB) milling is recommended because it avoids the mechanical stresses that can initiate delamination at the bonded interface while producing smoother optical facets. The fabricated waveguides can then be characterized using end-fire coupling with lensed fibres operating near 1550 nm, and the propagation loss can be determined using the cut-back method. Propagation losses between 2 and 5 dB/cm have previously been reported for InGaAsP-on-insulator waveguides of comparable dimensions [23], providing a suitable basis for efficient nonlinear operation over the waveguide lengths considered in this work.

The final stage is the experimental demonstration of four-wave mixing. A pump operating in the C-band near 1550 nm and a tunable signal are coupled into the waveguide, and the generated idler at $\lambda_i = (2/\lambda_p - 1/\lambda_s)^{-1}$ is measured while varying the pump, signal wavelength detuning. Recording the conversion efficiency across the tuning range enables the parametric gain bandwidth and phase-matching condition to be evaluated. Successful agreement between experiment and simulation would validate both the bonded InGaAsP-OI platform and the waveguide design methodology developed throughout this thesis, providing the final step towards the realization of practical nonlinear photonic devices.

6.4 Final Remarks

This thesis has investigated InGaAsP-on-insulator from two complementary perspectives—the materials and process perspective of heterogeneous integration, and the design perspective of nonlinear waveguide engineering—and has demonstrated that the platform is technically viable for both fabrication and nonlinear optical function. The fabrication studies established the mechanism and sensitivity of interfacial delamination, providing a clear path for process improvement. The waveguide simulations demonstrated that InGaAsP-OI can support efficient FWM with a nonlinear coefficient competitive with silicon-on-insulator in compact waveguides operating at telecommunications wavelengths.

The broader significance of this work lies in the material choice. InGaAsP has been a

workhorse of telecommunications for decades—in lasers, amplifiers, and detectors—precisely because its bandgap can be engineered for operation at 1.3–1.55 μm with monolithic active-passive integration. The InGaAsP-OI architecture investigated here aims to extend this established material system into the domain of chip-scale nonlinear photonics, adding strong optical confinement and dispersion engineering to the existing palette of InGaAsP functionality. The results of this thesis suggest that the principal obstacle is not the material or the nonlinear device design, but the reliability of the bonding process. Solving this fabrication challenge is therefore the single highest-leverage step toward realising the full potential of InGaAsP-on-insulator as a platform for integrated nonlinear photonic circuits.

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